LAVA

Computational Framework for Launch, Ascent, and Vehicle Aerodynamics*

Kiris at al.
AIAA-2014-0070

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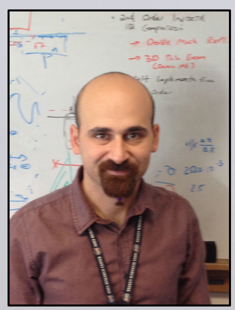
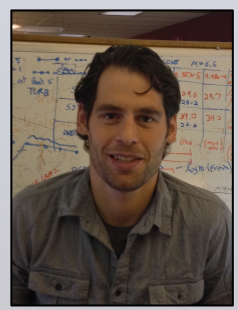




Jeff Housman ***Mike Barad*** ***Emre Sozer*** ***Christoph Brehm*** ***Shayan Moini-Yekta***

Applied Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, June 10, 2014

Introduction

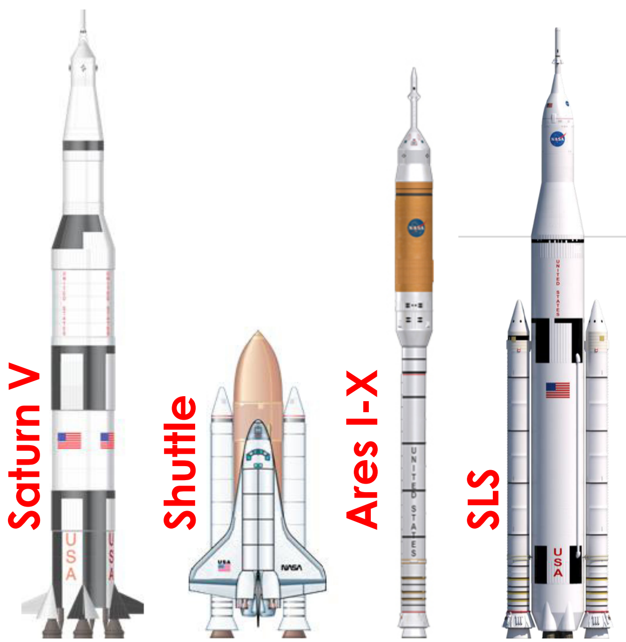
OBJECTIVE

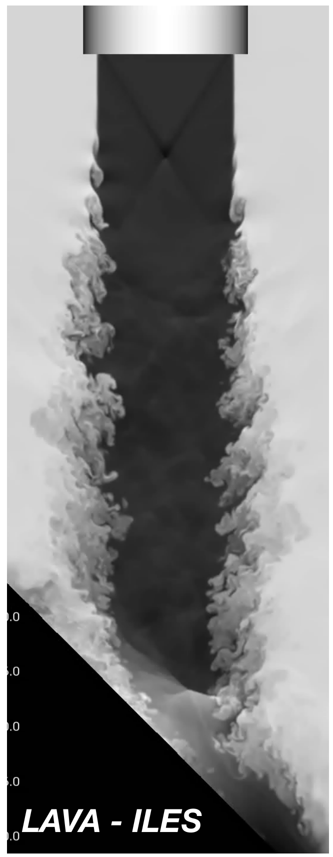
Provide CFD support for space launch vehicles

- ***Launch*** *Environment*
  - *Pressure & Thermal*
  - *Acoustic Prediction*
- ***Ascent*** *&* ***Vehicle Aerodynamics***

CHALLENGES

- *Geometric Complexity*
- *Complex Physics*

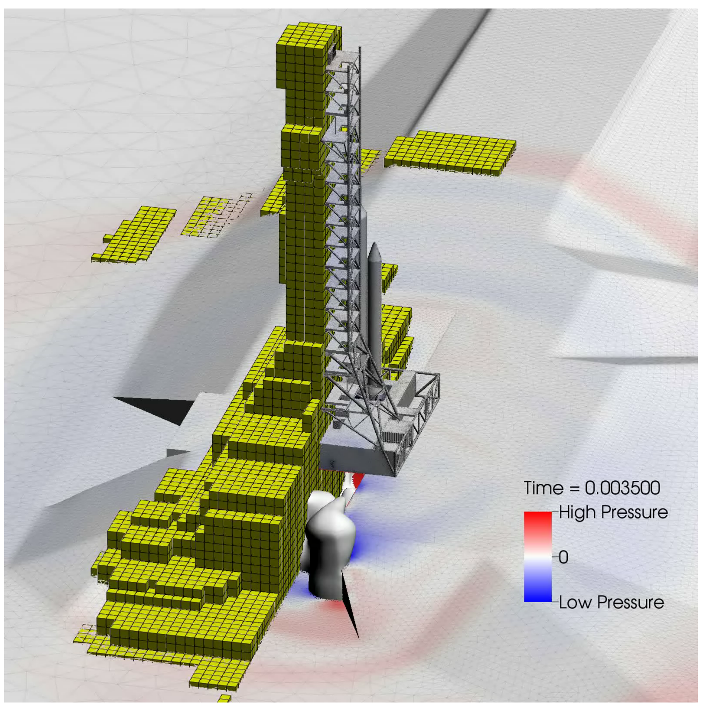




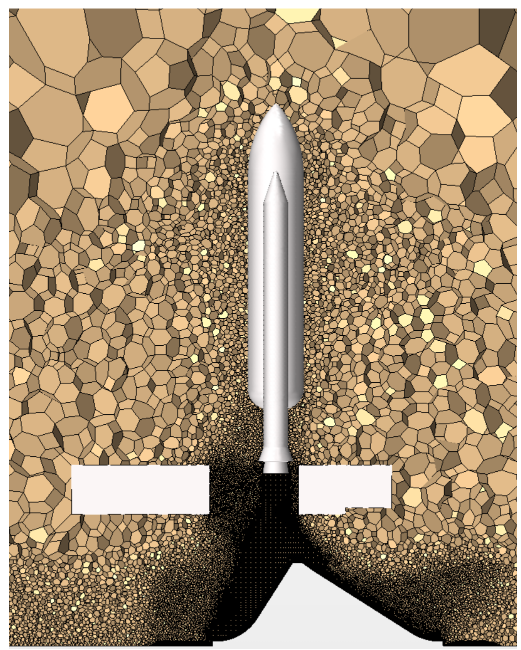
Introduction

Launch Ascent & Vehicle Aerodynamics (LAVA) Framework

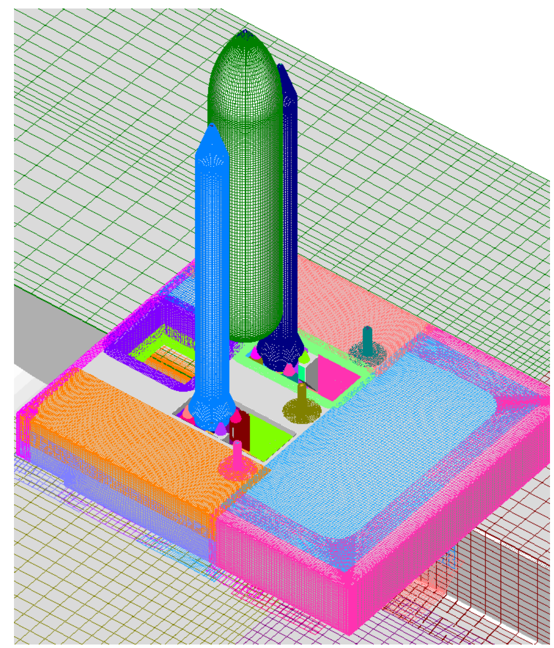
- Highly flexible with respect to computational mesh
  - Block-structured Cartesian meshes with Adaptive Mesh Refinement (AMR) and Immersed-Boundary (IB)
  - Unstructured arbitrary polyhedral meshes
  - Structured curvilinear overset meshes
- Overset coupling of different mesh types



Cartesian AMR



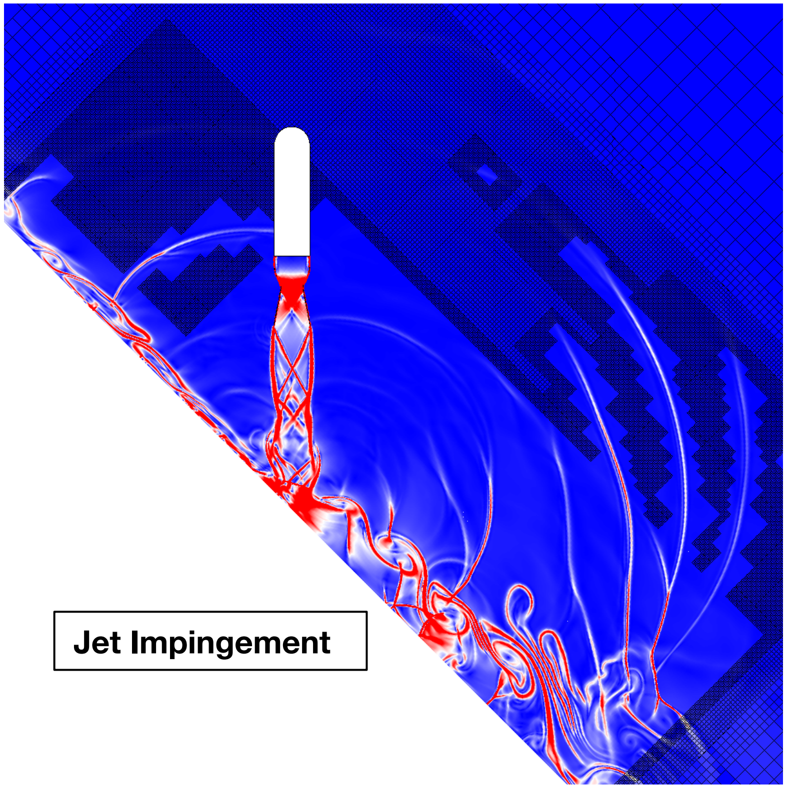
Unstructured Arbitrary Polyhedral



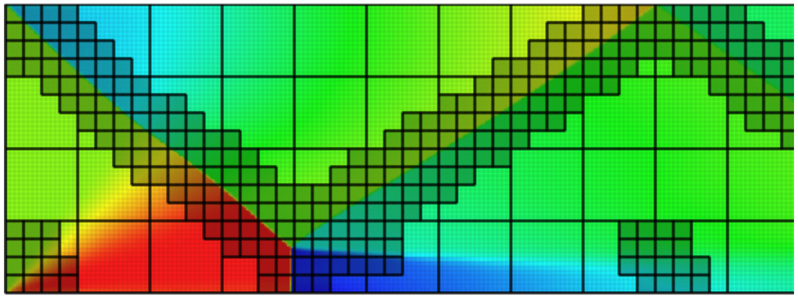
Overset Structured Curvilinear

Block-Structured Cartesian

- Density based compressible Navier-Stokes formulation
- 2nd order spatial and temporal accuracy
- Preconditioning for low speed flows
- Multi-Species formulation
- SA and SST turbulence models and DES
- Implicit time-integration with dual-time stepping for time dependent problems
- Parallel with MPI
- Block-Structured Cartesian grid
- Adaptive mesh refinement (AMR) for tracking flow features with local refinement (gradient, entropy adjoint, and geometry based)
- Automatic volume grid generation requiring only a surface triangulation
- Higher-order schemes available*
- Roe, AUSMPW+, central and van Leer convective flux formulations
- Line relaxation linear solver



Jet Impingement



Shock Reflection in a Rectangular Channel

Block-Structured Cartesian

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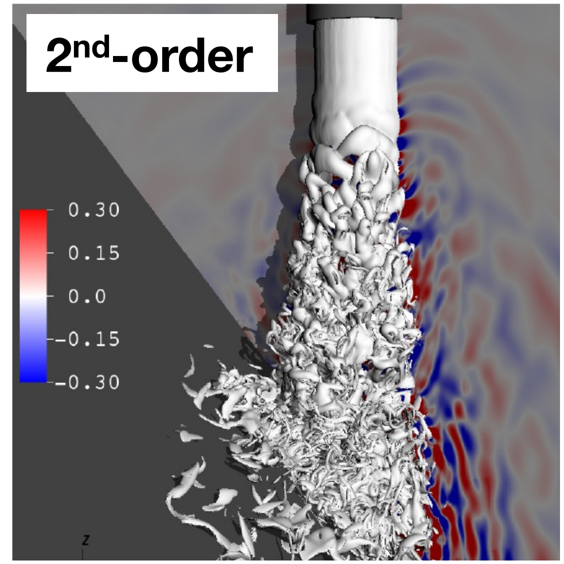
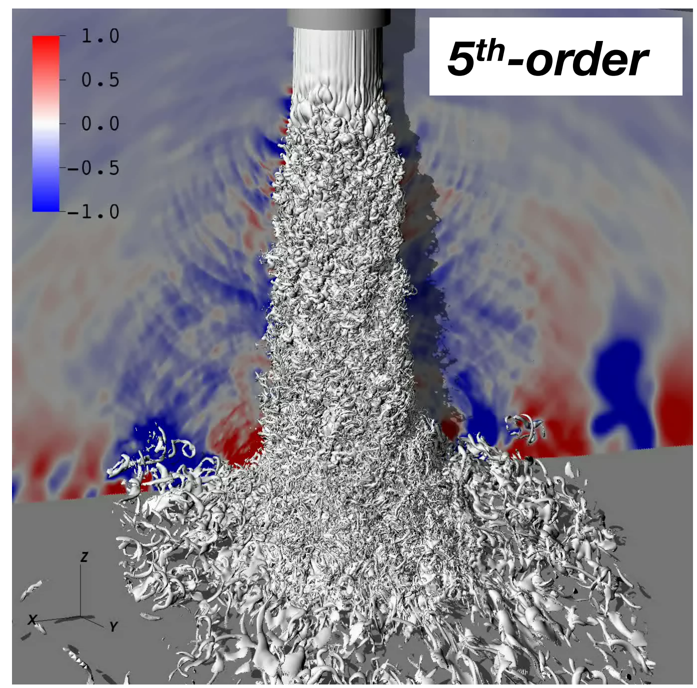
*Brehm et al. AIAA 2014-1278

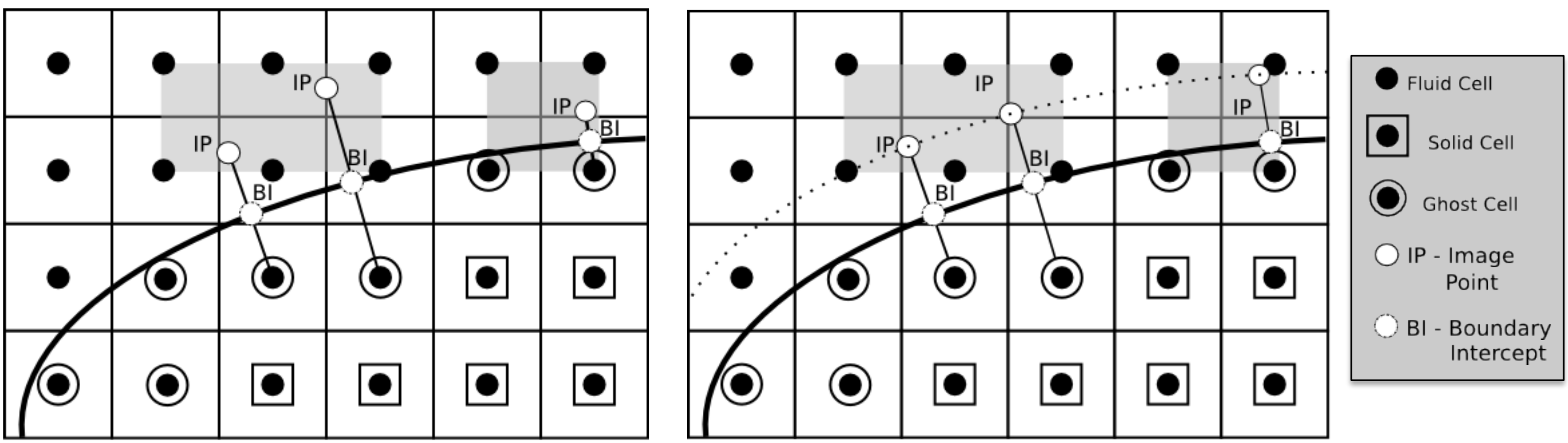
Jet Impingement





Cartesian Immersed-Boundary

- Sharp interface immersed-boundary representation of geometry
- Image points: either mirrored (left) or fixed distance (right)
- Interpolation to image points from fluid interior (tri-linear or linear least-squares)
- Boundary condition imposed on “ghost cells”
- Requires fast parallel algorithms:
  - Inside-outside testing by multi-resolution binning
  - Exact distance to surface triangulation (including point to plane and point to edge cases)
- Excellent for highly complex geometry, and works well with AMR

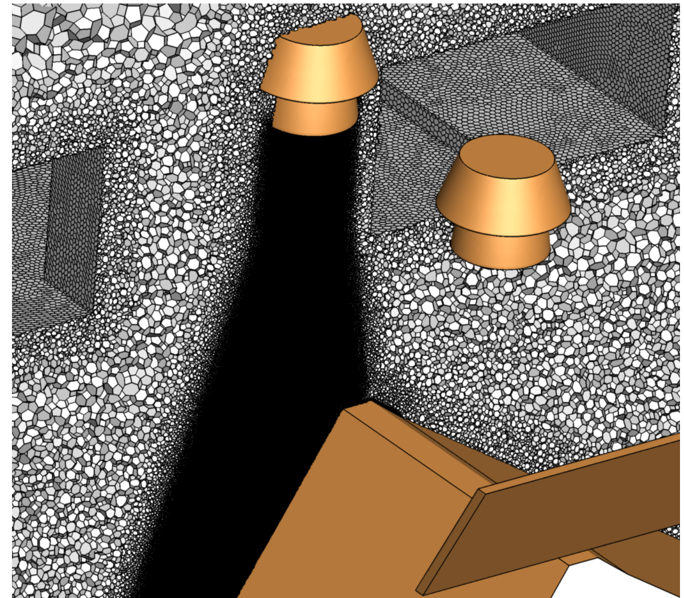


Mirrored ***Fixed Distance***

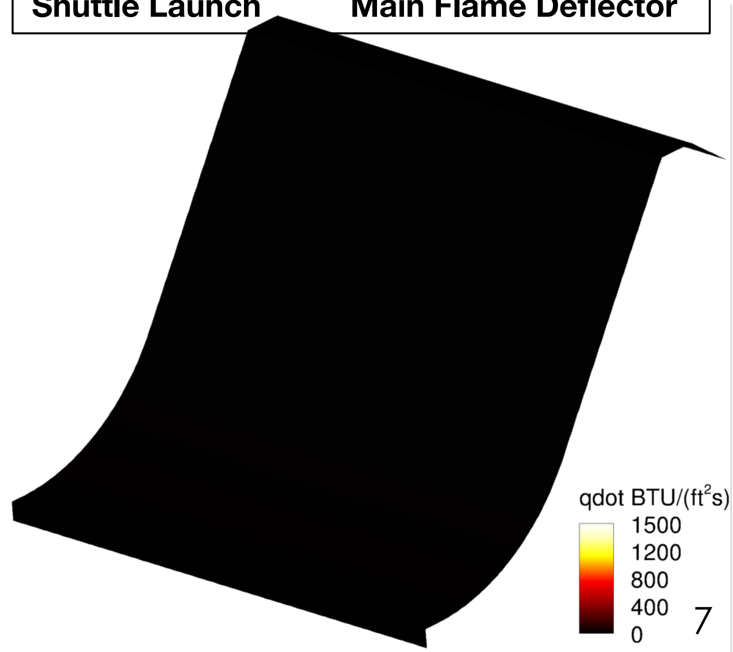
Unstructured Arbitrary Polyhedral

- Density based compressible Navier-Stokes formulation
- 2nd order spatial and temporal accuracy
- Preconditioning for low speed flows
- Multi-Species formulation
- SA and SST turbulence models and DES
- Implicit time-integration with dual-time stepping for time dependent problems
- Parallel with MPI
- Arbitrary polyhedral cell types*
- GMRES linear solver
- Roe, AUSMPW+, and van Leer convective flux formulations
- Conjugate heat transfer

*Sozer et al. AIAA 2014-1440



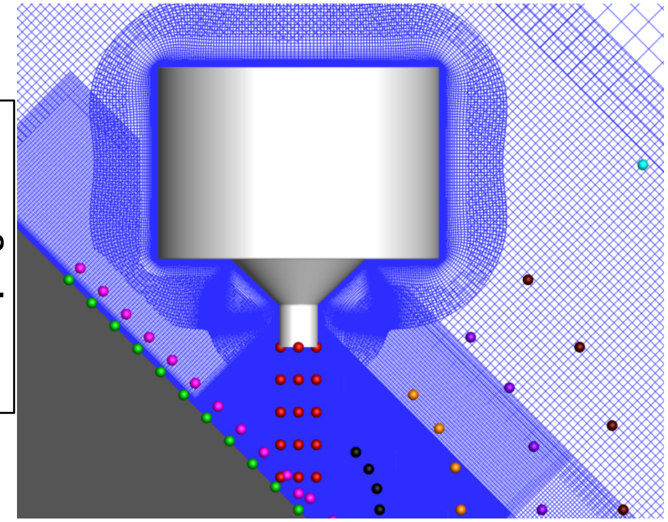
Shuttle Launch Main Flame Deflector

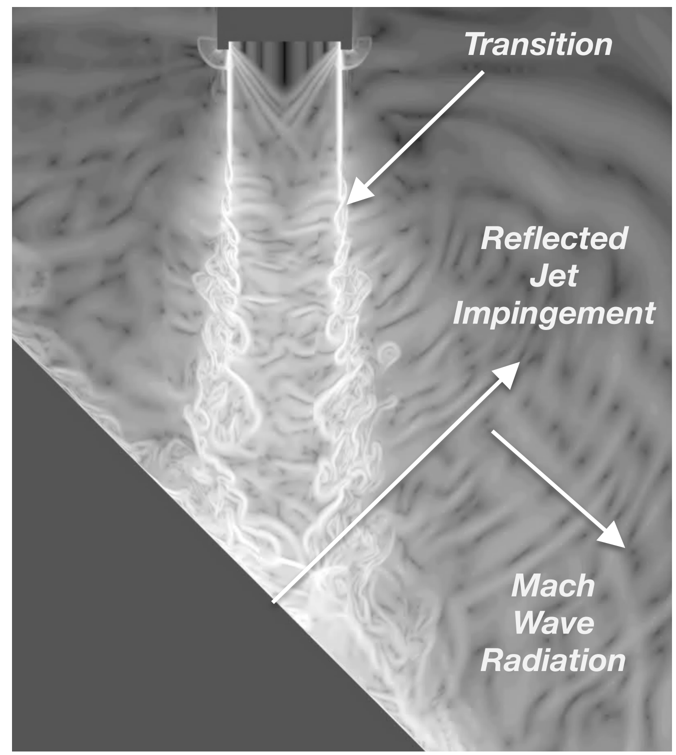


Structured Curvilinear

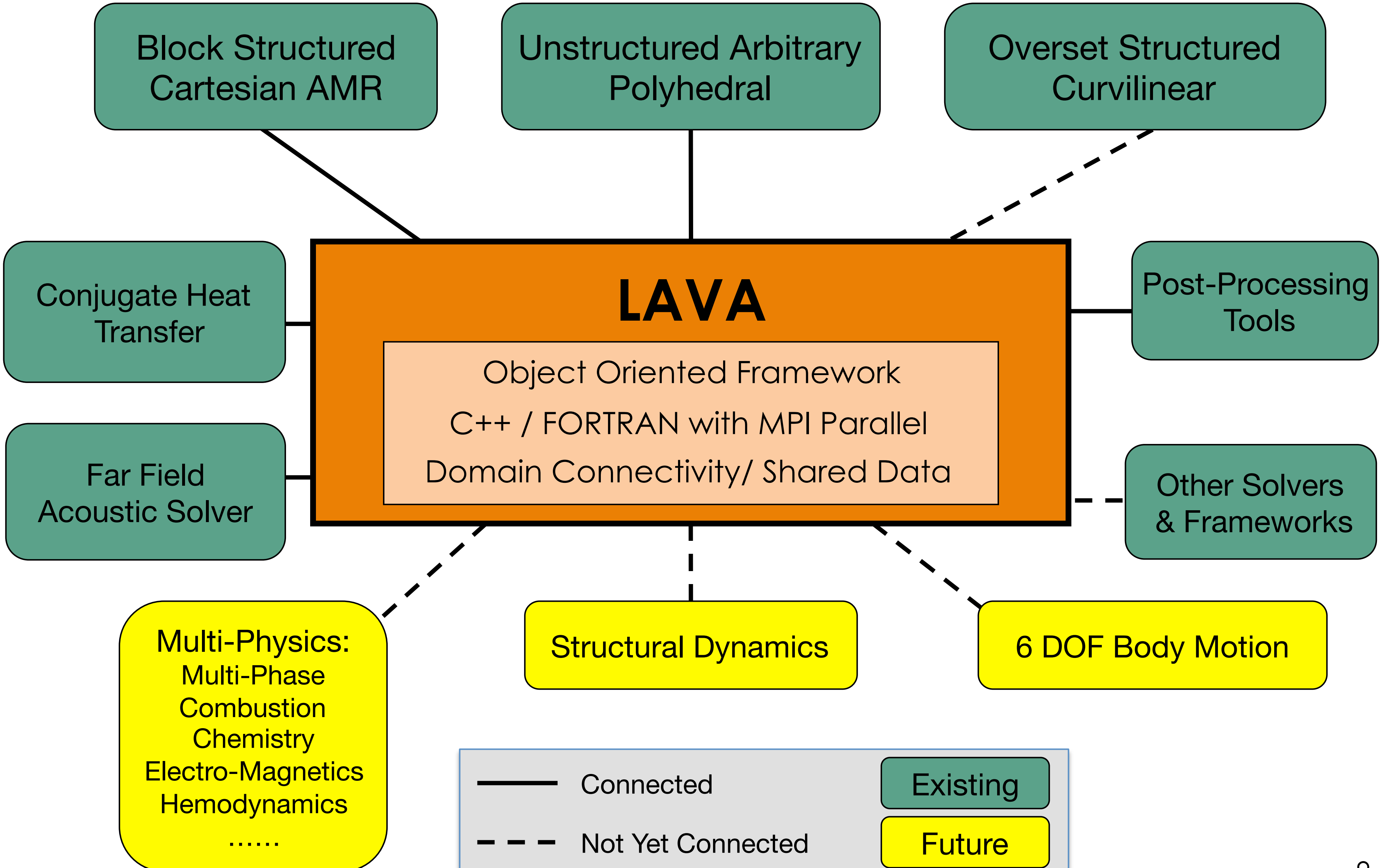
- Density based compressible Navier-Stokes formulation
- 2[nd] order spatial and temporal accuracy
- Preconditioning for low speed flows
- Multi-Species formulation
- SA and SST turbulence models and DES
- Implicit time-integration with dual-time stepping for time dependent problems
- Parallel with MPI
- Curvilinear structured overset grids
- Line relaxation linear solver
- Roe, and central convective flux formulations
- Multi-phase flows

Jet Impingement



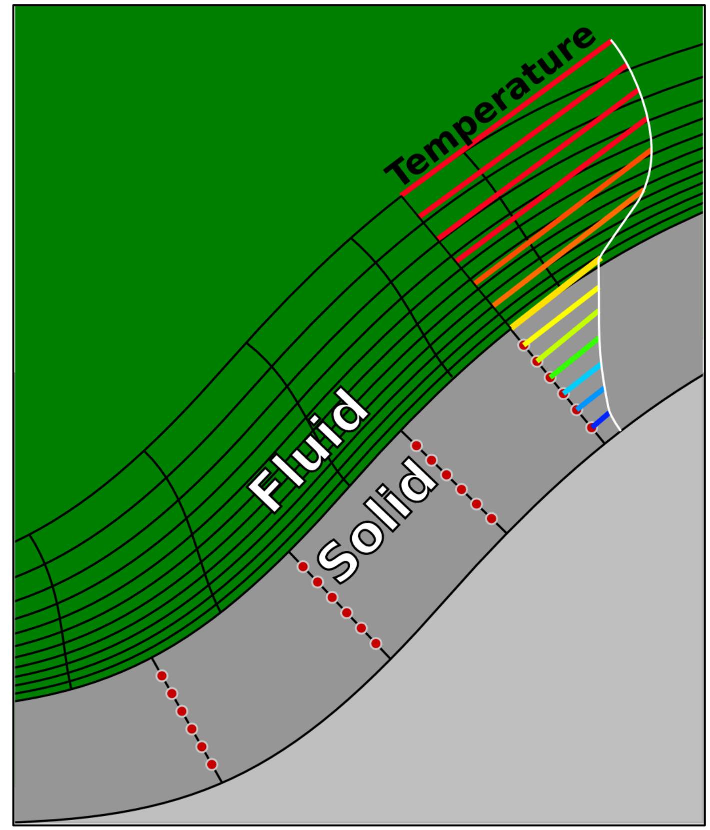


LAVA Infrastructure Design

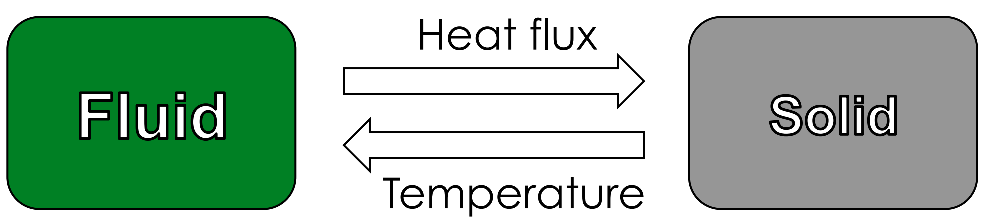


Conjugate Heat Transfer

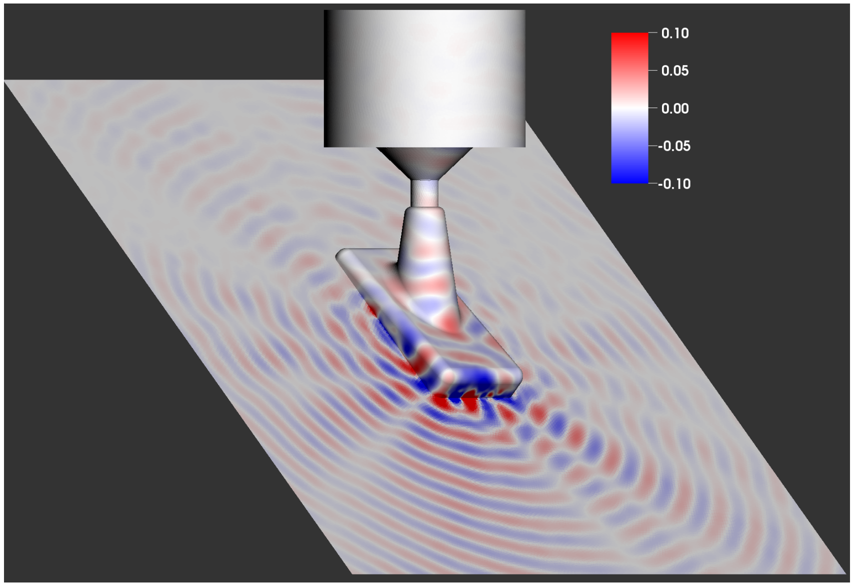
- **Fluid domain (LAVA):**
  - Arbitrary polyhedral unstructured mesh
  - Polygonal prism boundary layer mesh
  - 3D Navier-Stokes equations

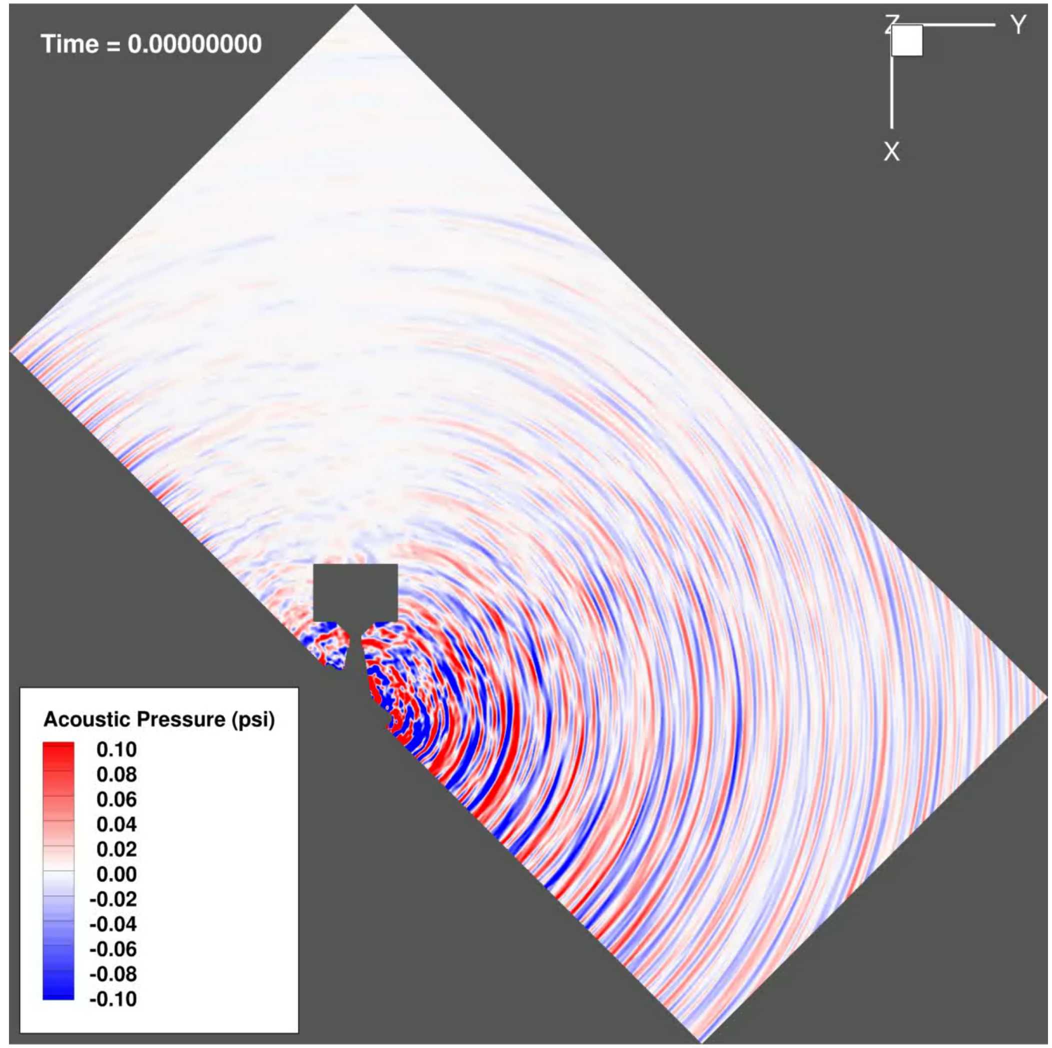


- **Solid domain:**
  - 1D, unsteady heat conduction equation
  - Along rays for each fluid mesh face on the surface
  - Solid back assumed insulated
- **Coupling:**
  - **Two-way information exchange at each sub-iteration**



Far Field Acoustics Solver





- Time-History of LAVA CFD data recorded on embedded acoustic surface.
- FFT used to transform data to frequency domain.
- Linear Helmholz and Ffowcs William-Hawkings (FWH) formulations are available for acoustic propagation.
- Acoustic pressure at any observer location outside the acoustic surface can be evaluated in either the frequency or time-domain.

LAVA Applications

- **Launch Environment**
  - Launch Pad Pressure Environment
  - Main Flame Deflector (MFD) Heating Analysis
  - Launch Pad Acoustics
- **Heavy Lift Vehicle Ascent Aerodynamics**
  - Steady Analysis for SLS Ascent Trajectory
  - Unsteady Ascent Aerodynamics
  - Plume Induced Flow Separation (PIFS) for Saturn V
- **Aeronautics Applications – Vehicle Aerodynamics**
  - D8 "Double Bubble" Concept Aircraft
  - 1st AIAA Sonic Boom Prediction Workshop
  - SOFIA Cavity Acoustics
  - AIAA Workshop on **B**enchmark Problems for **A**irframe **N**oise **C**omputations (BANC-III)
    - Landing Gear Noise
    - Slat Noise

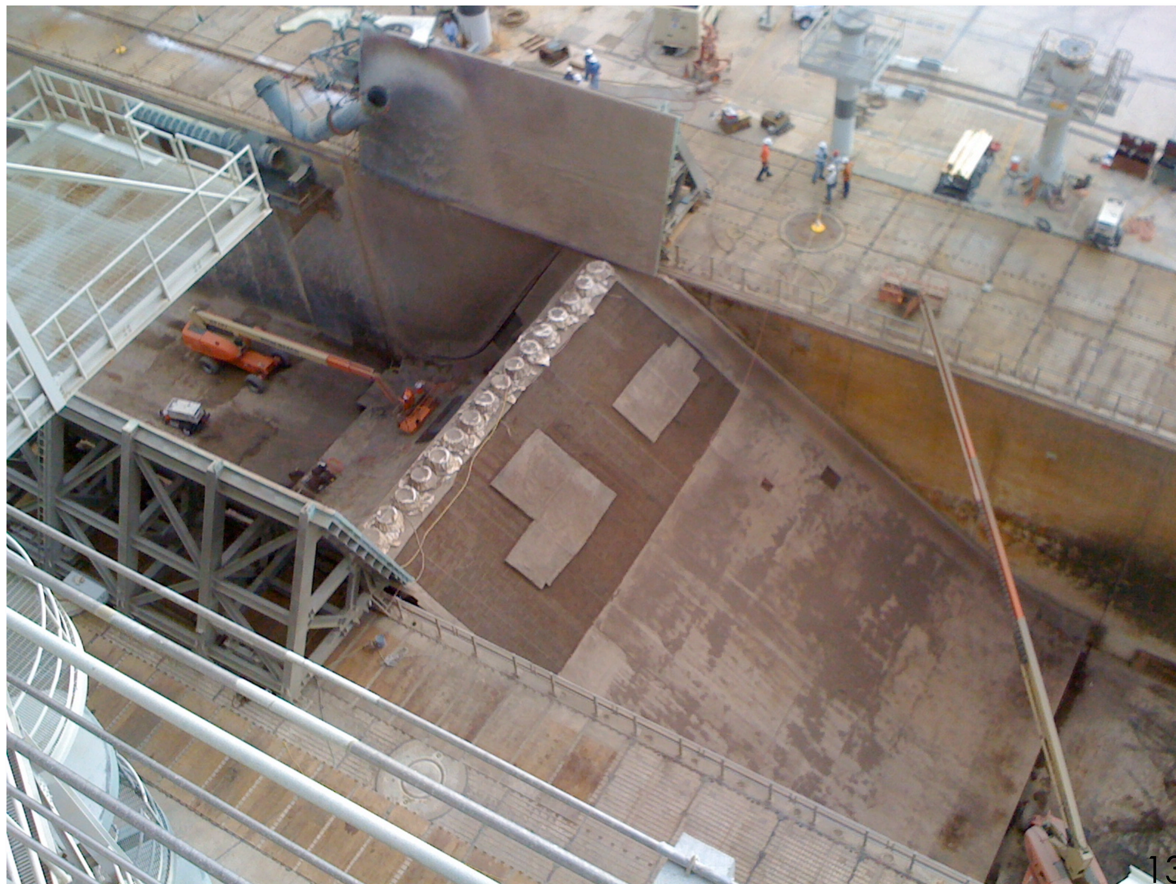
*Basic Verification and Validation (V&V) studies were reported by Moini-Yekta, et al. (**AIAA 2013-2448**)*

Launch Environment

- Significant resources have been spent to develop the materials and structures to withstand the harsh conditions of vehicle launches.
- The launch environment is highly complex in terms of geometric details and flow physics.

Computational fluid dynamics (CFD) support is essential in the analysis and design of the launch pad.

- Analysis of different vehicle and launch site configurations
- Provide time-dependent structural and thermal loading
- Large-scale time-dependent simulations during a rapid design cycle



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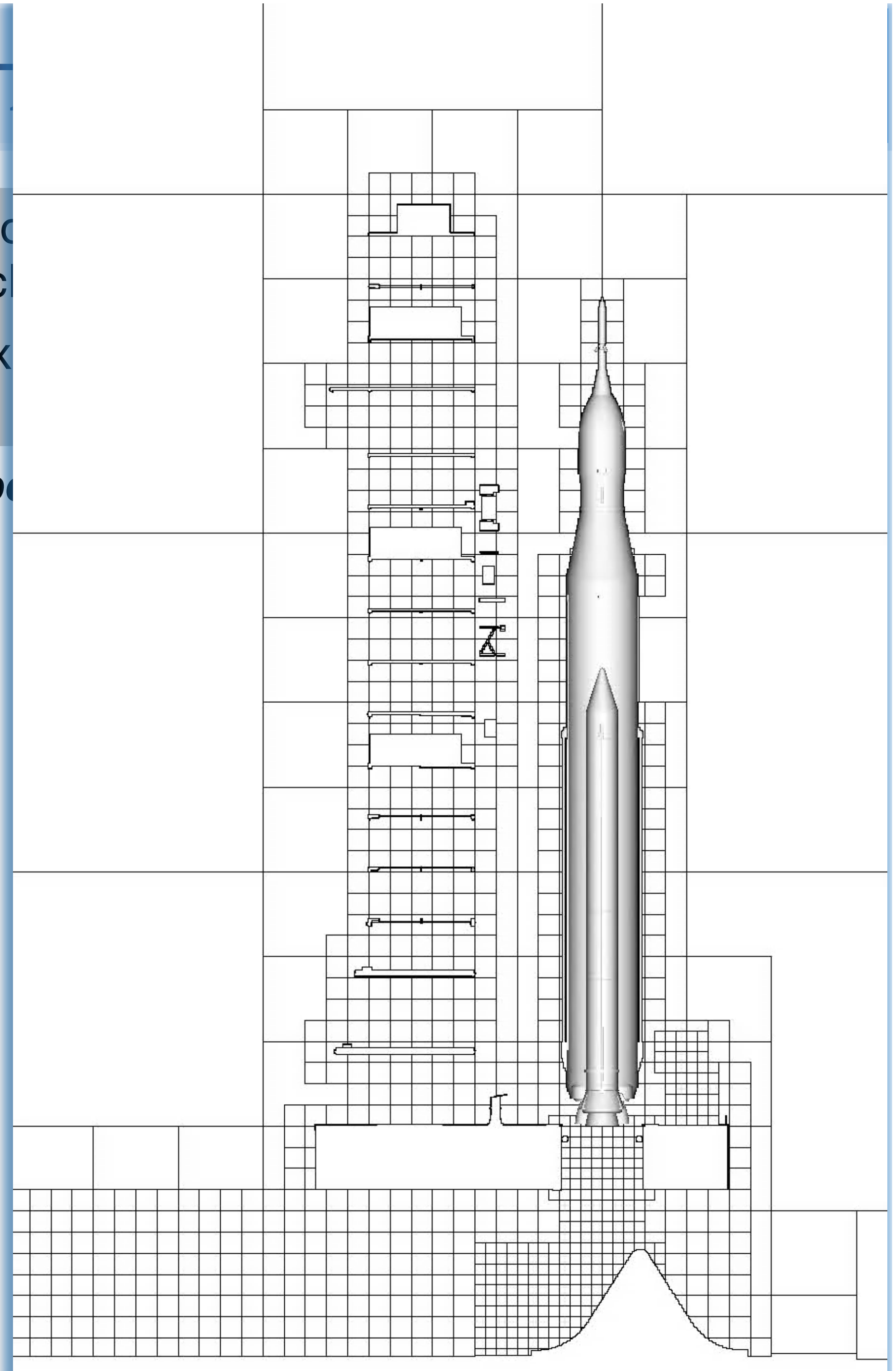

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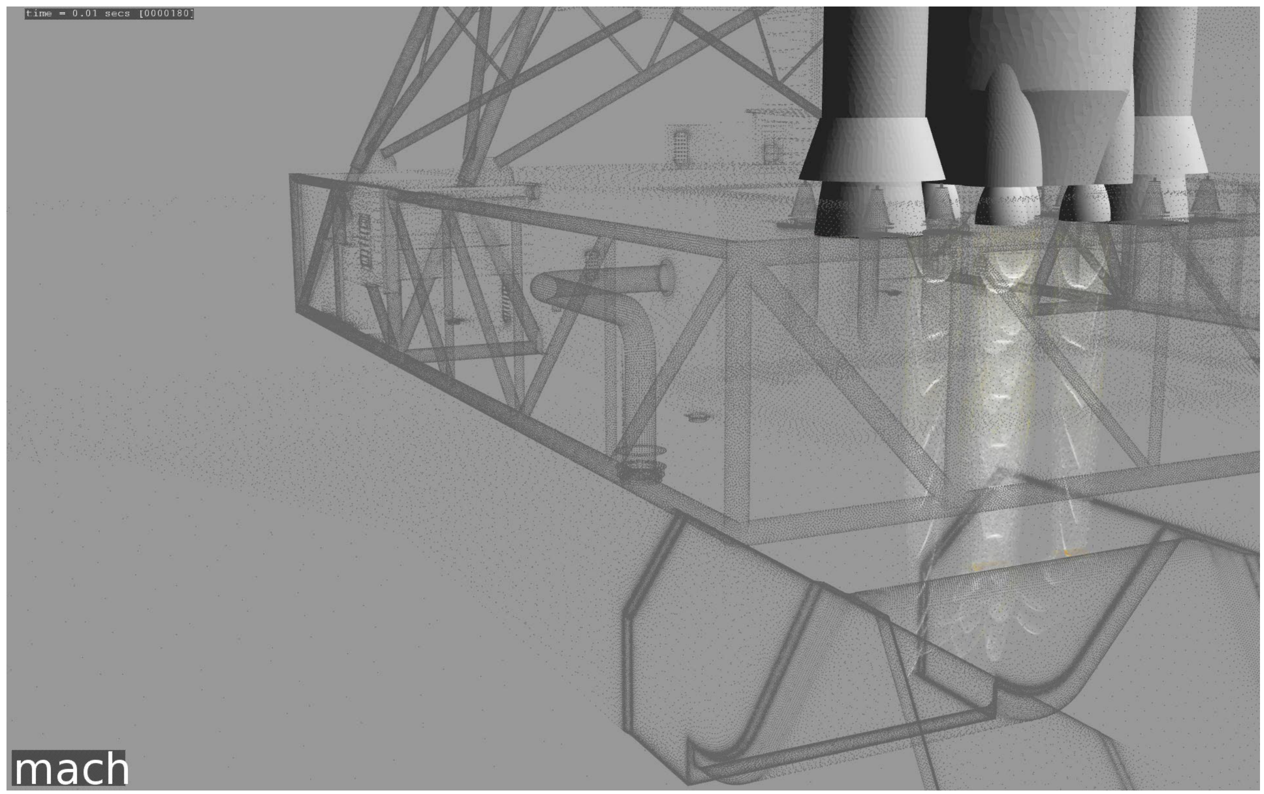

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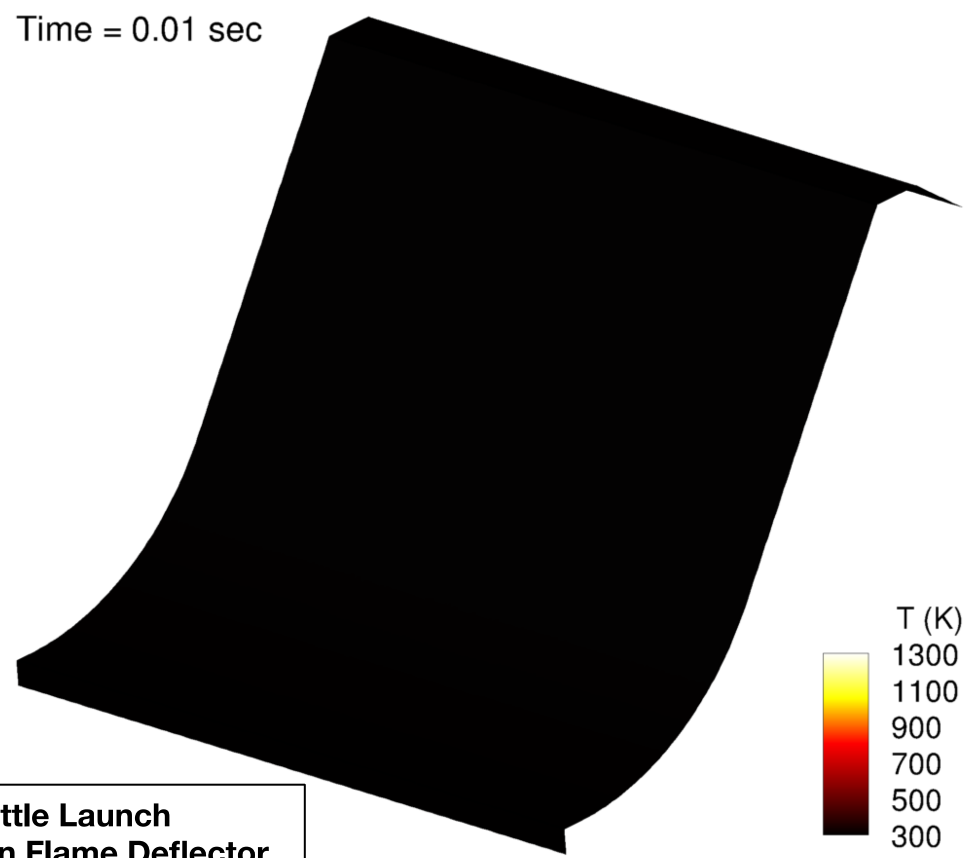
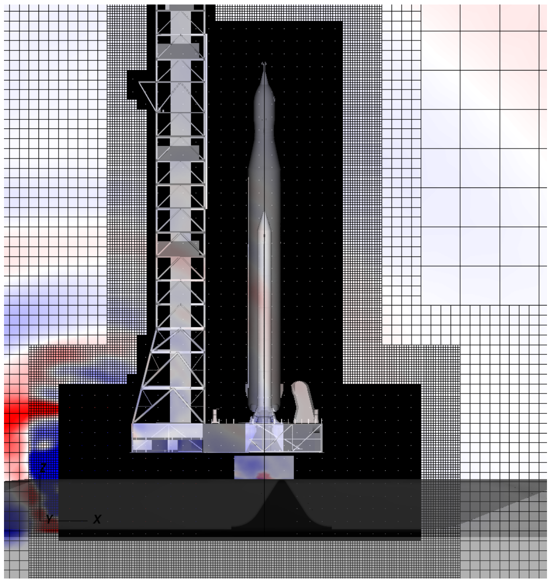
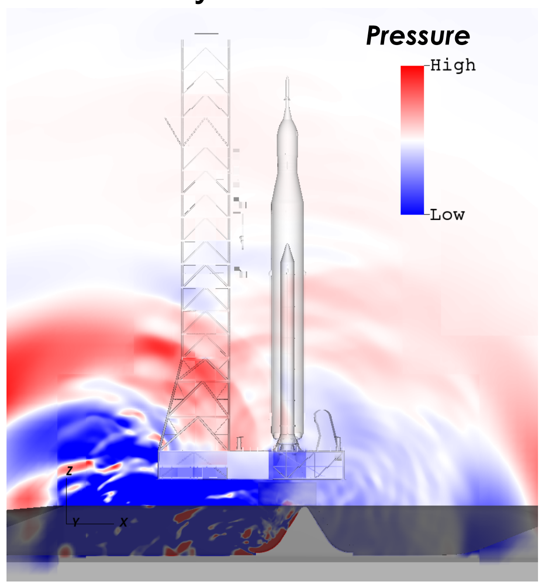


Shuttle Launch
Main Flame Deflector

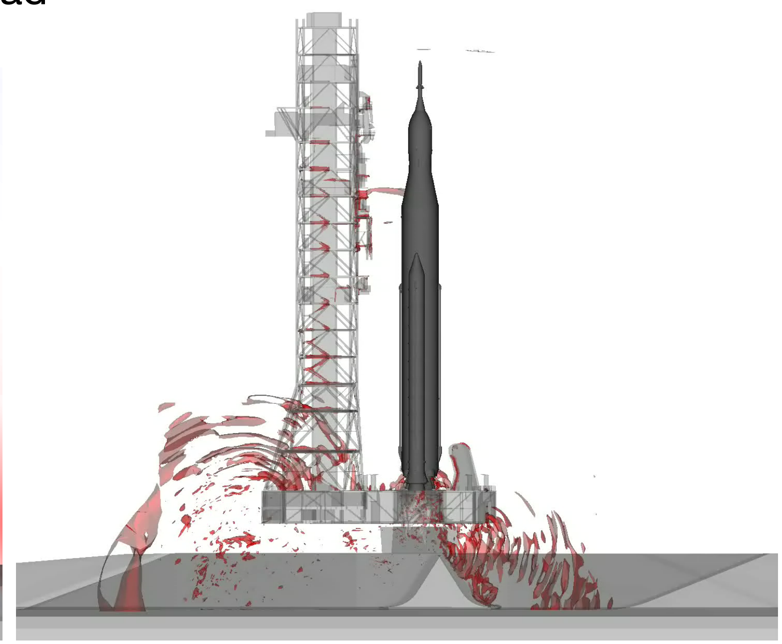
Launch Environment - Pressure

- **Physics:** Ignition Overpressure (IOP) & Duct Overpressure
- **Hardware:** Vehicle, Mobile Launcher (ML), and Launch Pad
- **Method:** Cartesian Immersed Boundary AMR

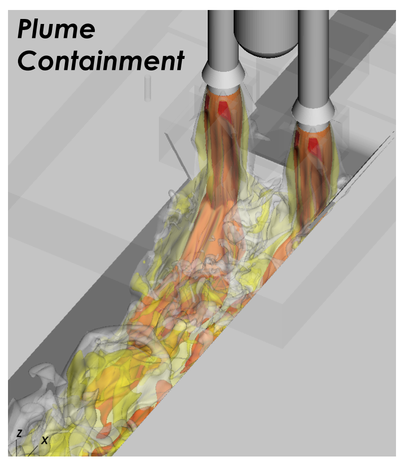




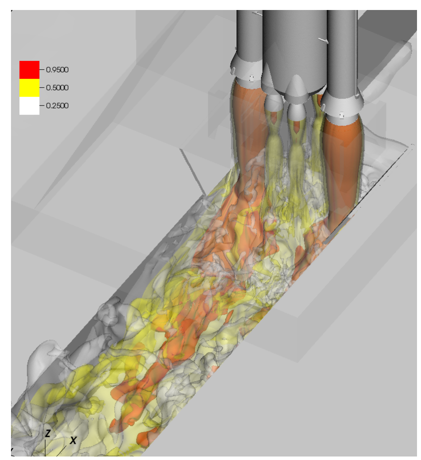
Pressure Gradient



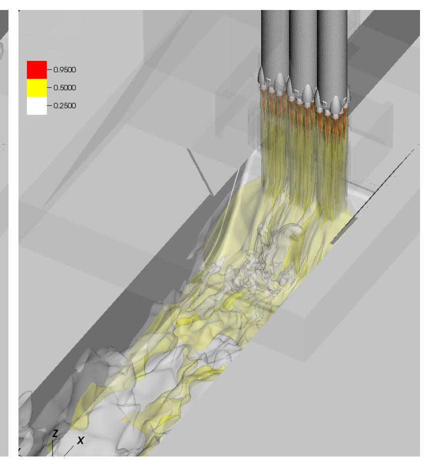
- 2^{nd} order in time, dual-time stepping ($dt_{physical}$= 3.5×10^{-5} sec)
- 2^{nd} order MUSCL with minmod flux limiter
- ~130 Million grid points with 7 grid levels
- Multi-species formulation with air, core-stage engine exhaust gas, and SRB exhaust gas
- Less than 5 days turnaround time with 900 cores



STS



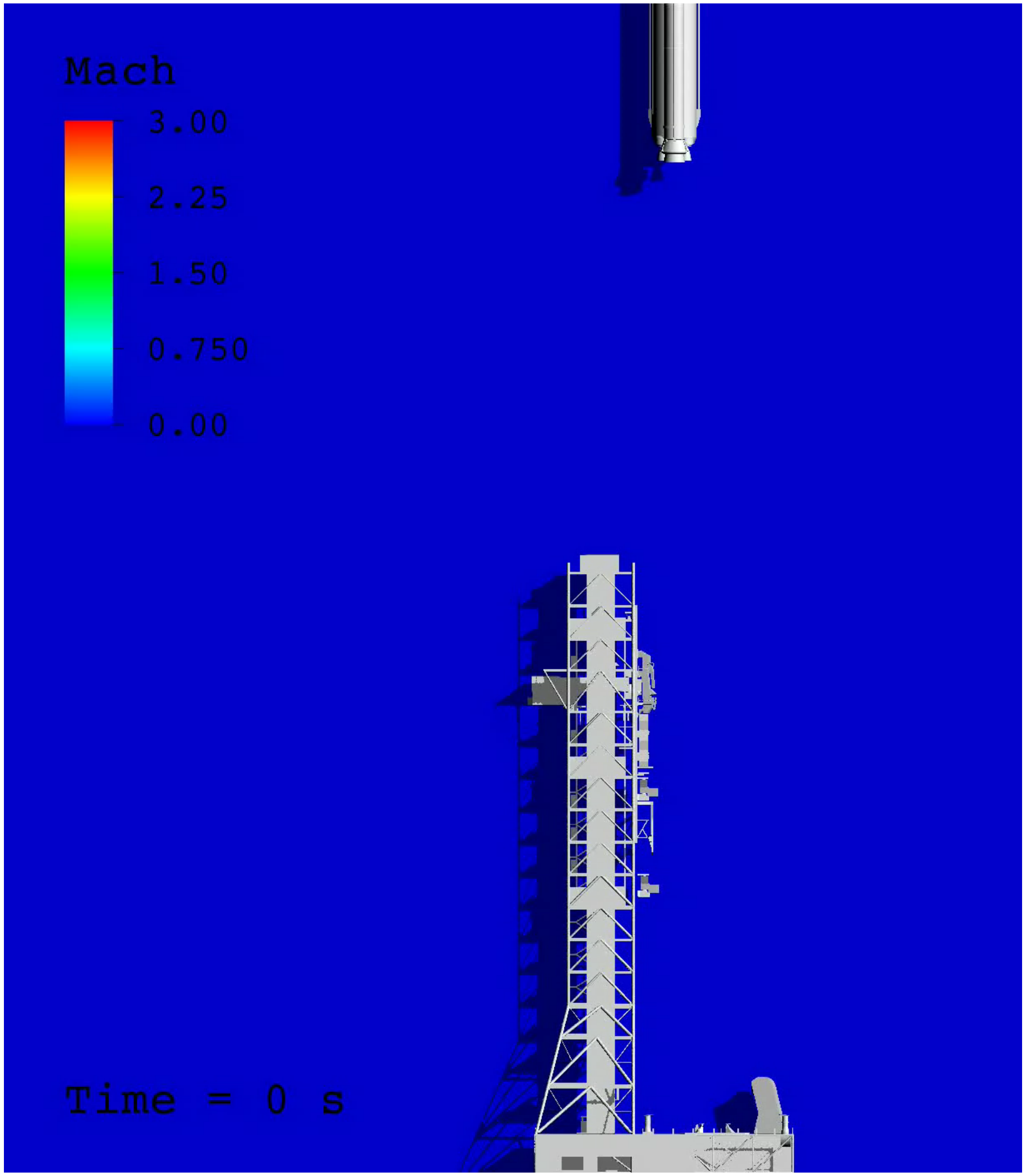
SLS

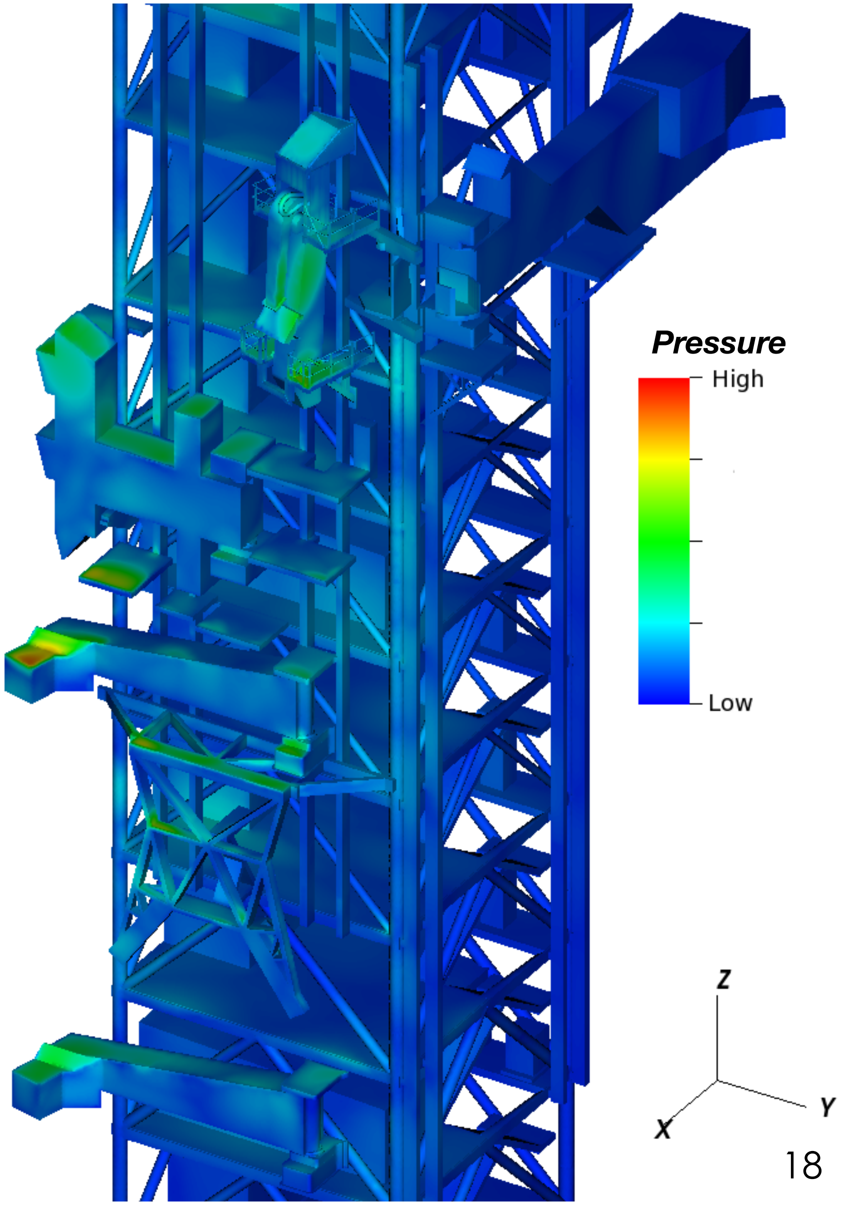


Falcon Heavy

Launch Environment - Pressure

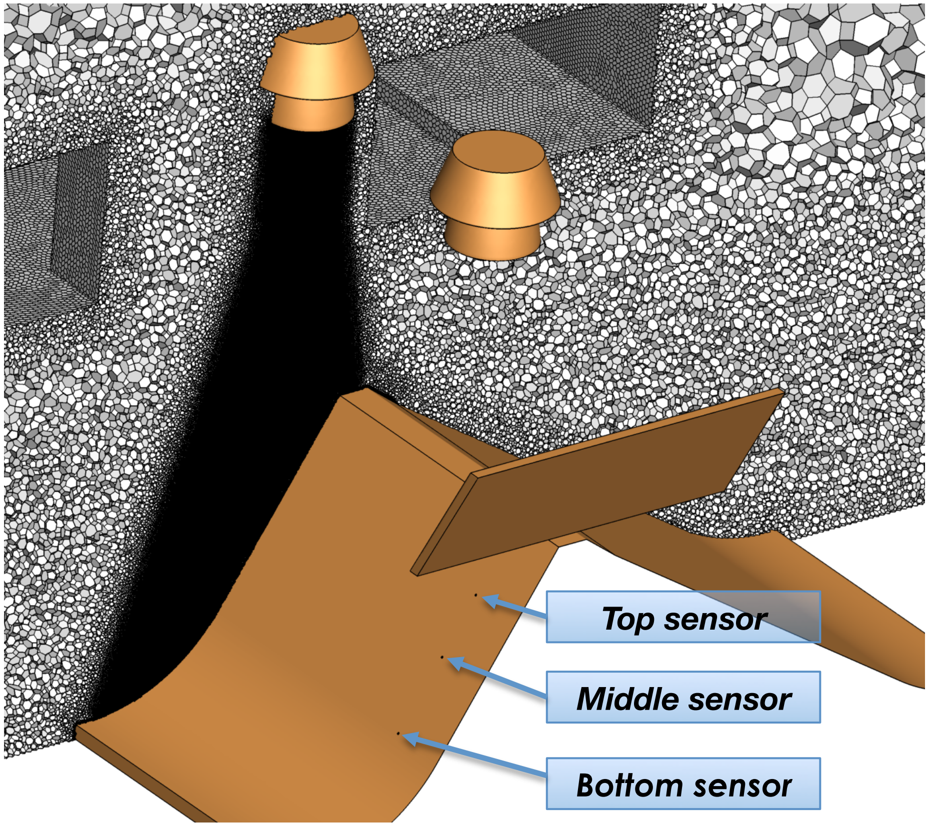
Cartesian Immersed-Boundary with Deteched Eddy Simulation (DES)





Launch Environment – Thermal

LAVA Simulations : STS -1

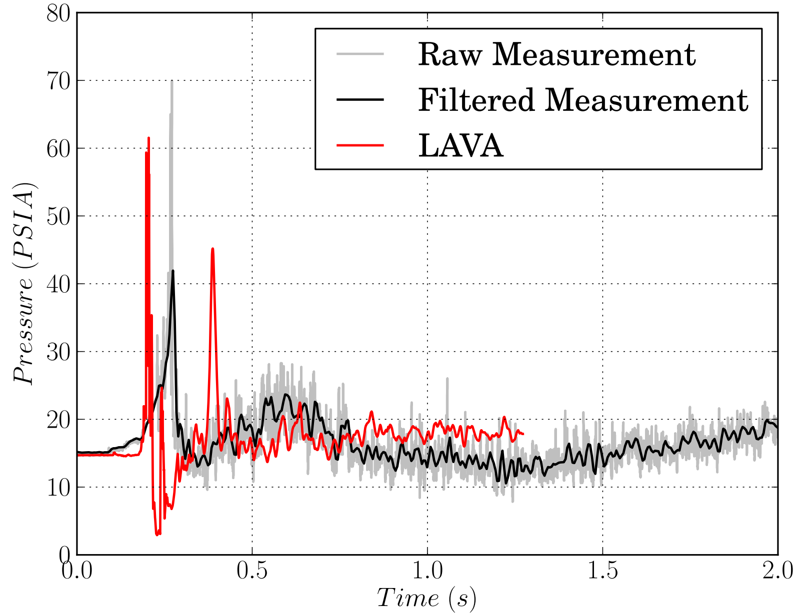


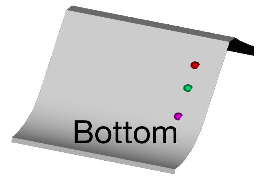
- Arbitrary polyhedral unstructured mesh (21 M cells)
- Polygonal prism boundary layer mesh ($y^+ < 1$)
- SA-DES Turbulence model
- Dt = 3.5e-5 secs with 20 subiterations

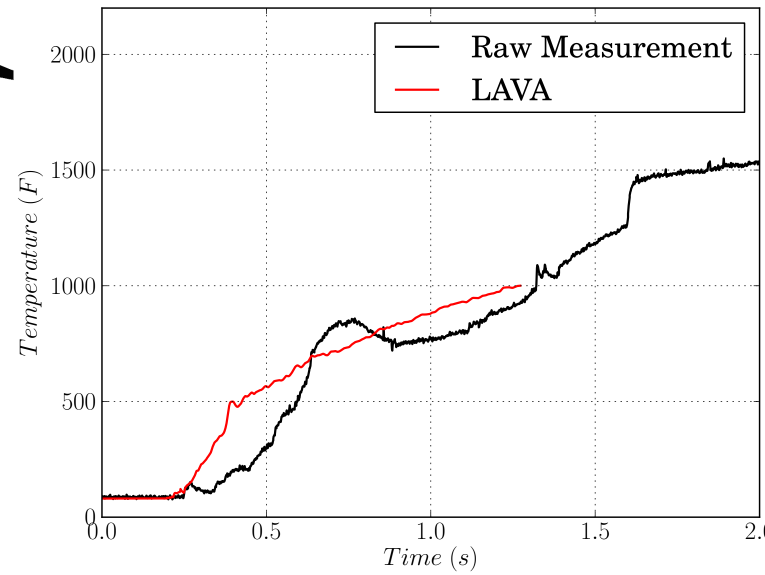
Flight Data: STS -135

- Unsteady SRB plenum data was used from STS-1. *Likely inconsistencies with STS-135*
- Water sound suppression system is not modeled. *May affect wave propagation speed*

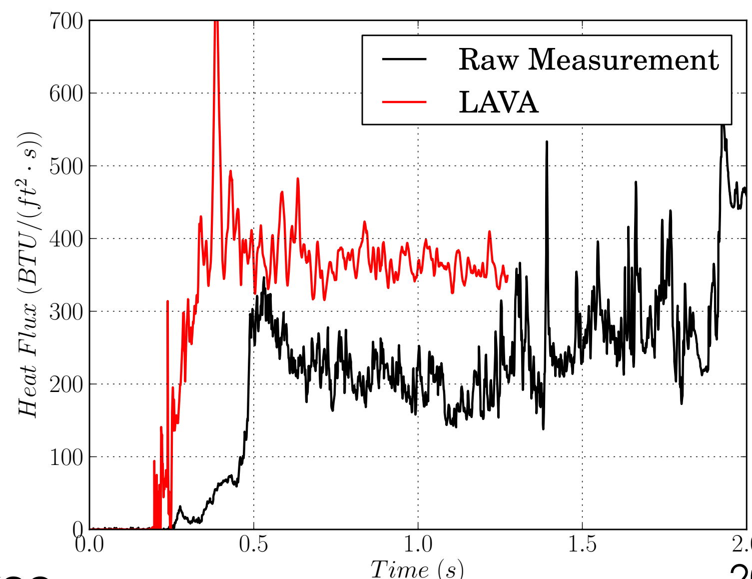
STS-135 :: Flight DATA & CFD - Bottom Sensor







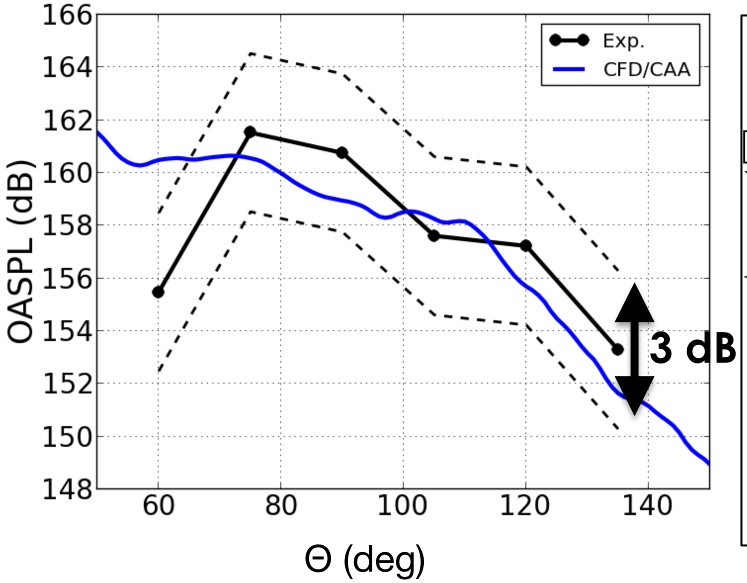
- Reasonable agreement with the measurements
  - Temporal discrepancy is observed, possibly due to water exclusion.
  - IOP wave amplitude is accurately captured.
  - Temperature predictions are very consistent.
  - Heat flux predictions are conservative within reasonable margin.
    - Large measurement uncertainty in heat flux

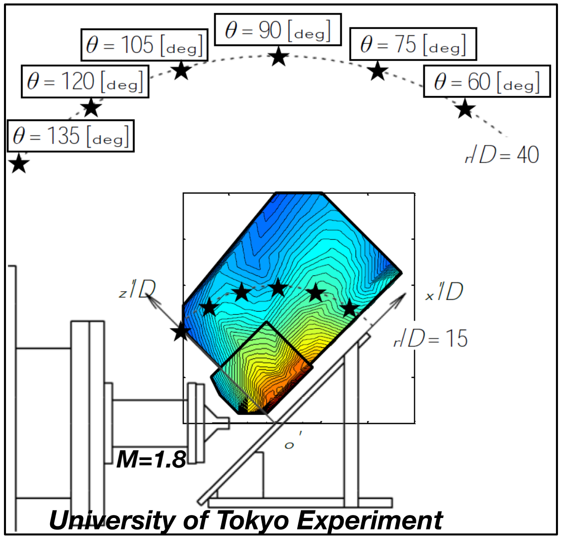


STS-135 flight data is provided by B. Vu and C. Parlier, NASA-KSC

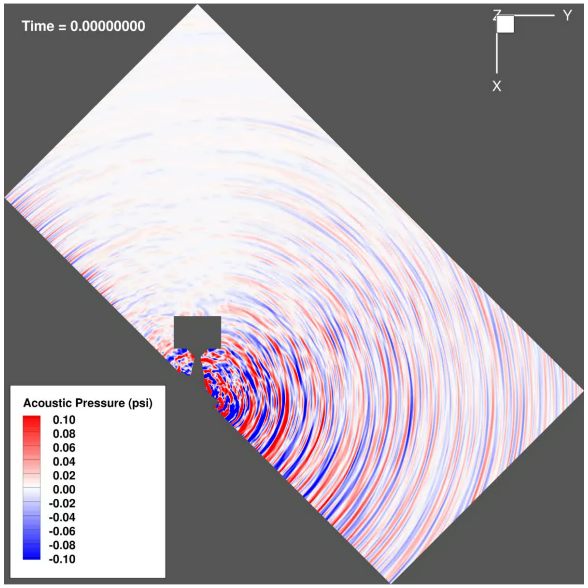
Launch Acoustics – *Validation*

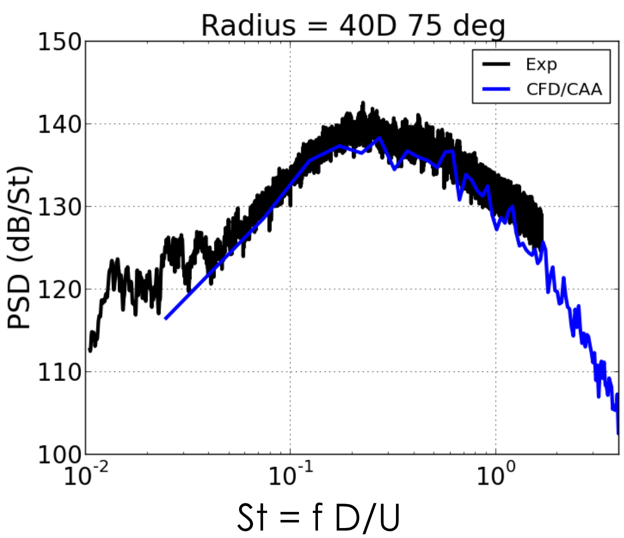
- OASPL predictions within 3 dB are obtained from 75 to 135 degrees.
- Good comparison in PSD observed at 75, 90, and 105 degrees

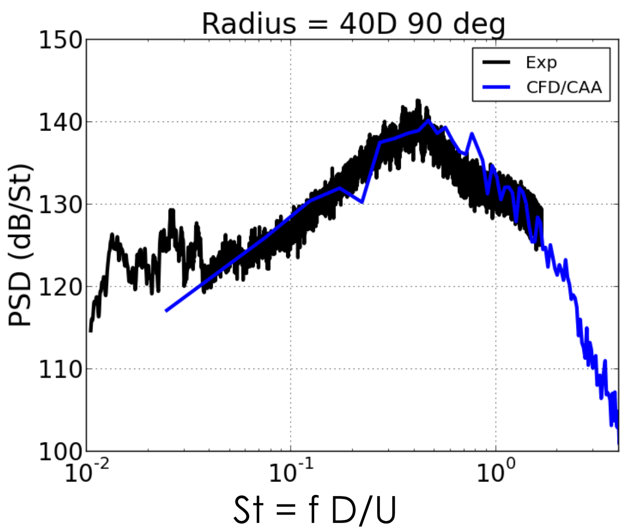


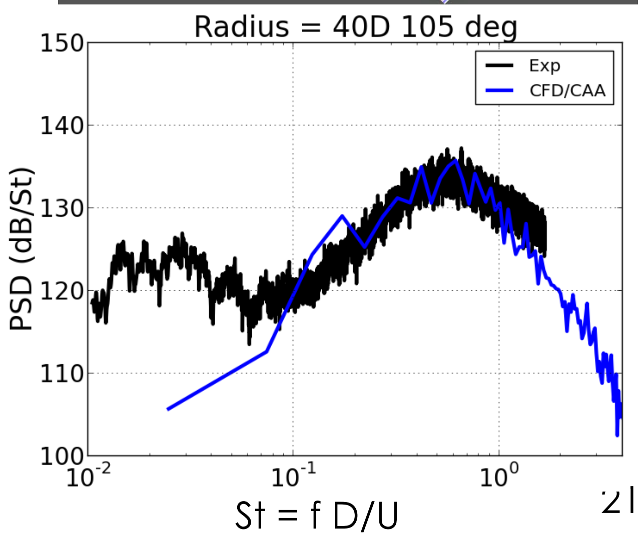


University of Tokyo Experiment
Nakanishi et. Al. AJCPP2012-129

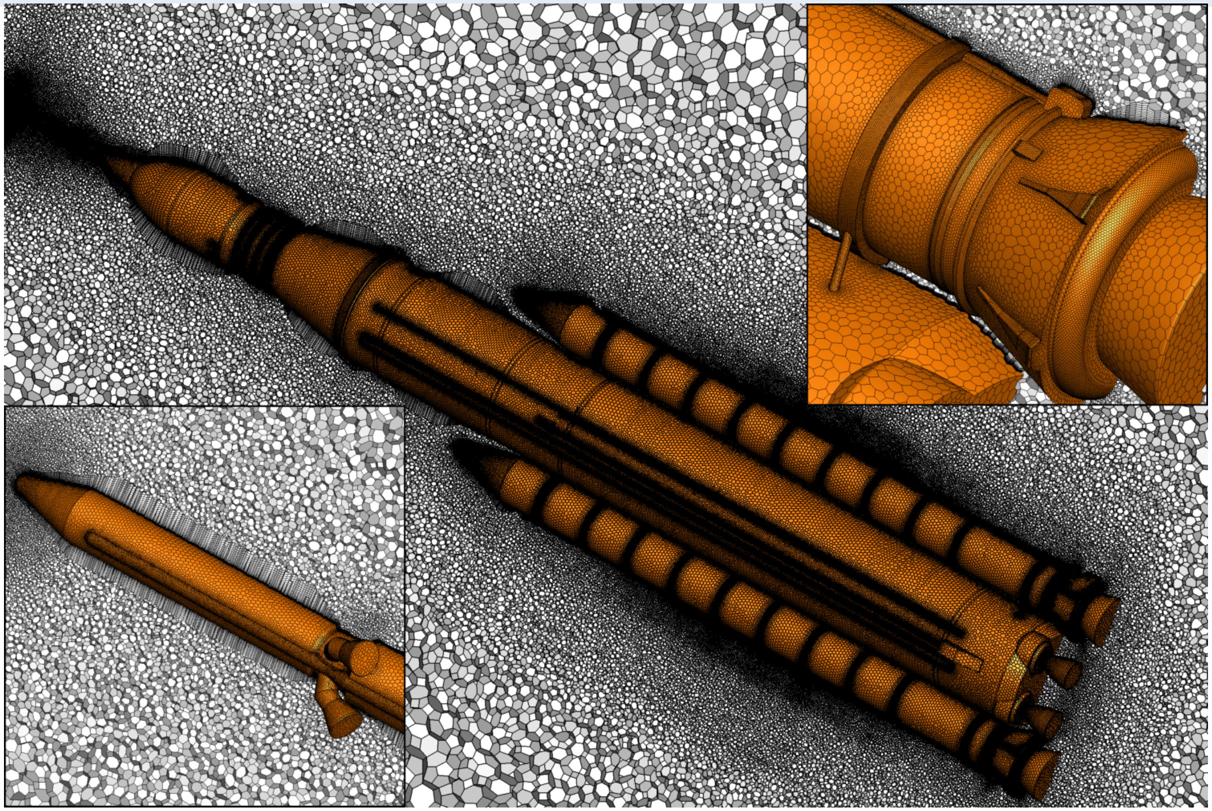


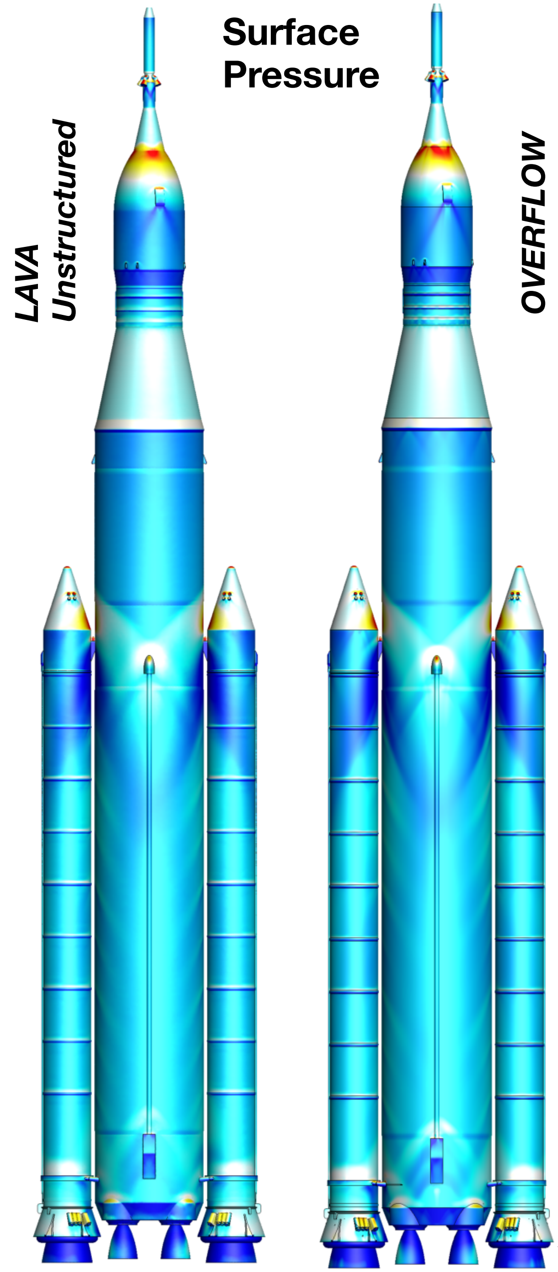






Space Launch Systems (SLS) Ascent Aero





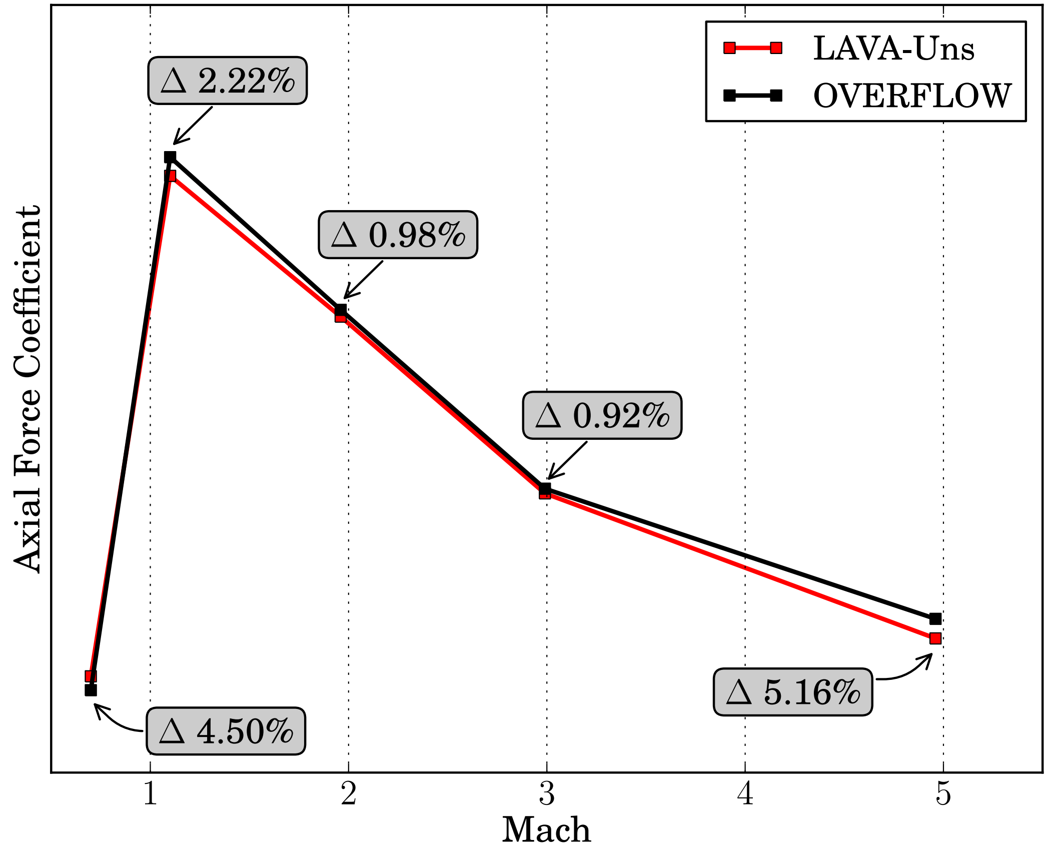
- 40 Million arbitrary polyhedral unstructured cells
- Polygonal prism layers near the wall ($y^+ < 1$)
- Steady calculations for a limited set of the SLS ascent trajectory points.
- Spalart-Allmaras one-equation turbulence model

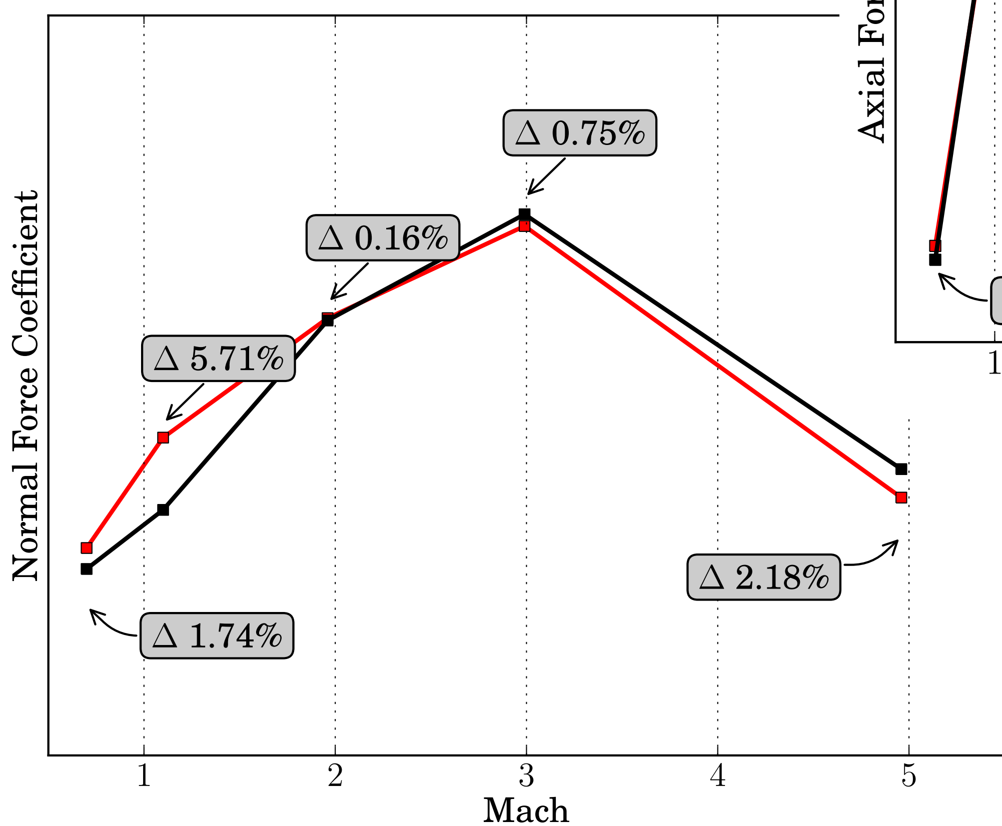
Blevins et al. **AIAA 2014-1253**

SLS Ascent Aerodynamics

Code-to-code comparison :
axial and normal force coefficients

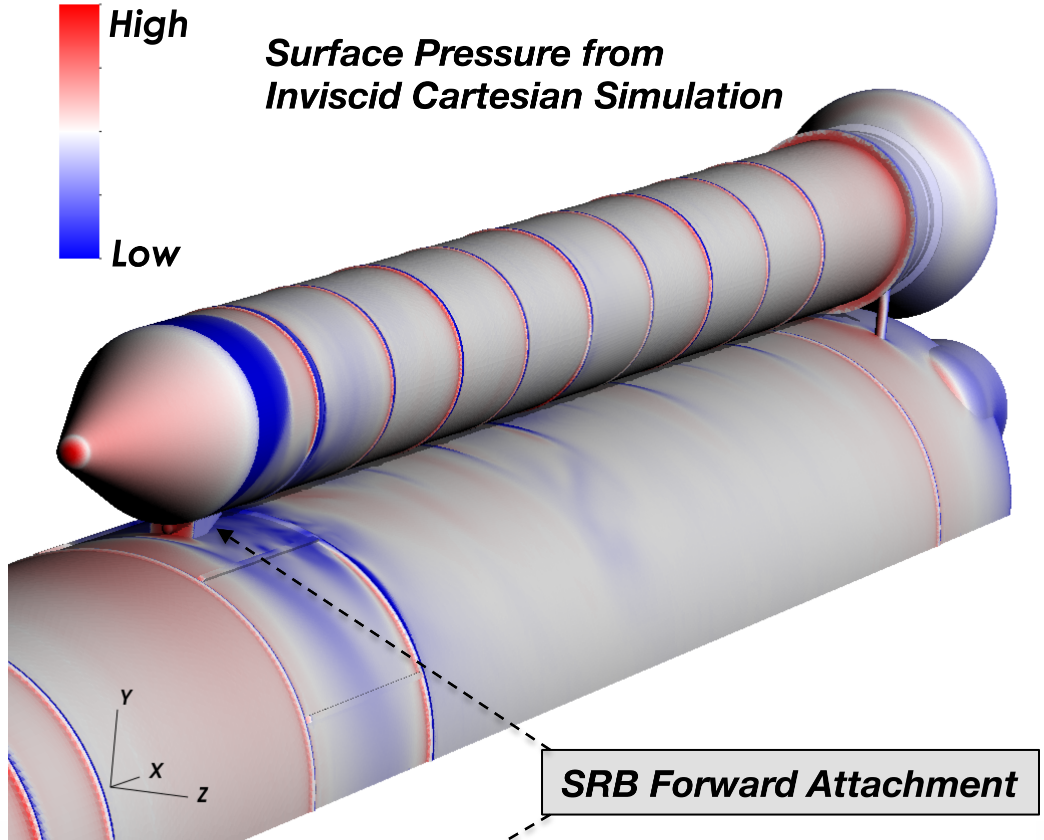
- ~5% difference between OVERFLOW and LAVA results

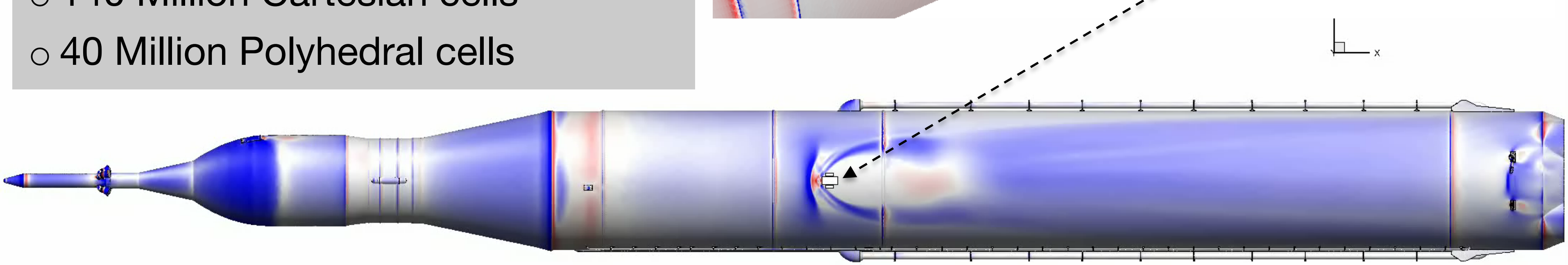




SLS Unsteady Ascent Aerodynamics

- Protuberances and attachment hardware may cause significant aerodynamic unsteadiness.
  - Cyclical loads and undesirable acoustic environment
- Time dependent viscous unstructured analysis and inviscid Cartesian analysis
- Rapid design analysis is possible with the Cartesian solver which eliminates time consuming mesh generation.
- 140 Million Cartesian cells
- 40 Million Polyhedral cells

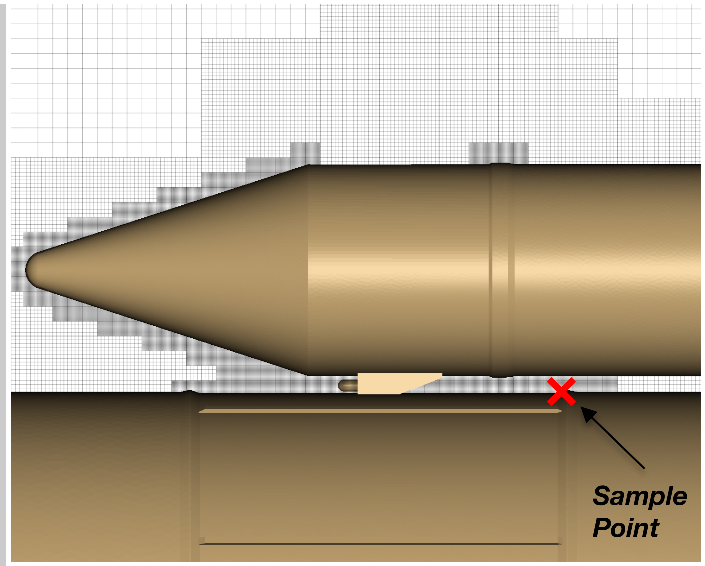




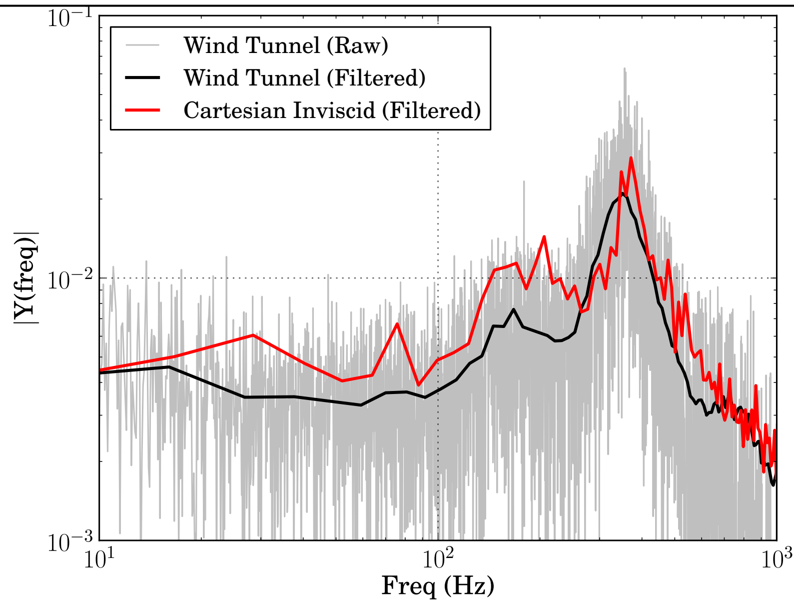
Skin Friction from Viscous Unstructured Simulation

SLS Unsteady Aerodynamics

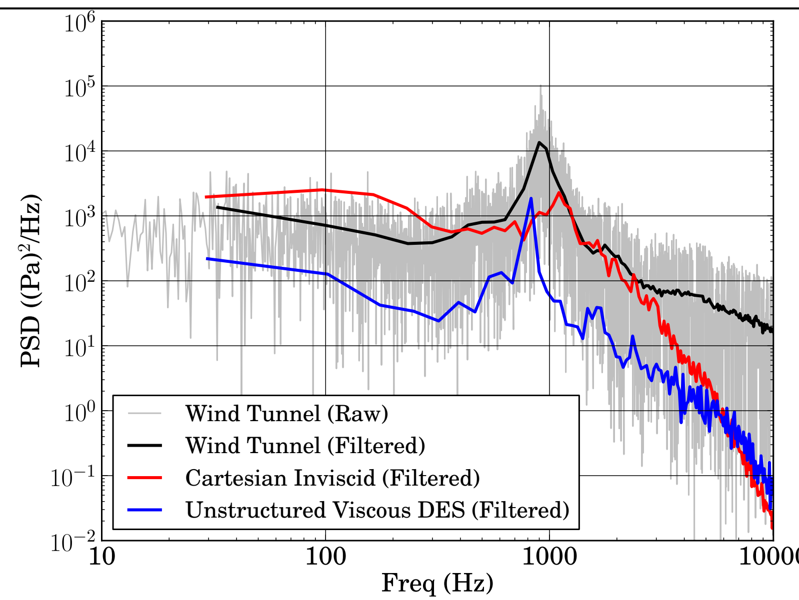
- Comparison of LAVA results and experimental data focused on oscillatory wake region behind the SRB forward attachment.
- Spectral amplitudes of pressure data between Cartesian inviscid LAVA results and NASA Langley TDT data compare well
- Power Spectral Density plots (PSD) from inviscid and viscous DES results compare well with NASA Ames UPWT data.



NASA Langley Transonic Dynamics Tunnel (TDT) Test Article



NASA Ames Unitary Plan Wind Tunnel (UPWT) Test Article

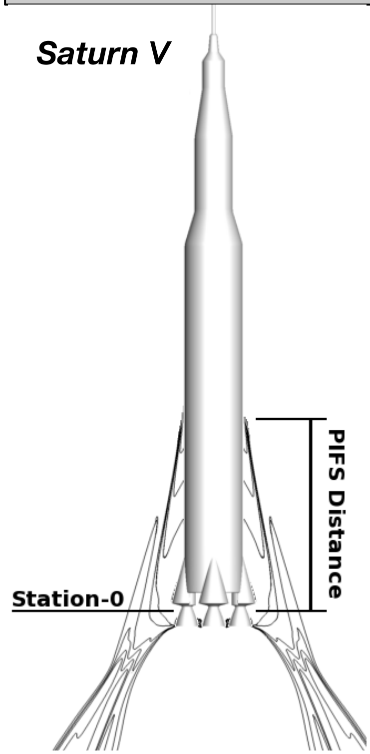


PLUME INDUCED FLOW SEPERATION (PIFS)

- Separation caused by an adverse pressure gradient.
- High pressure ratio $P_{exit}/P_{ambient}$ causes rapid plume expansion in downstream and radial directions.
- Plume expansion produces a blockage to the flow, an adverse pressure gradient, and flow separation.
- Flow recirculation entrains exhaust gas and convects it up the sides of the launch vehicle.
- Accurate predictions of PIFS distance are important for thermal protection and vehicle control authority.

Footage of Saturn V in flight, PIFS visible by extent of radiating exhaust gas

Saturn V



- **Flight Data:**
  - PIFS observed in flight data at Mach > 3.3 (**AS-506 Flight Evaluation Report, TM-62558**)
  - ***10% measurement uncertainty***
  - Reference **Station-0** located ~2.84 meters downstream of the base (see diagram)

- **LAVA CFD Simulations:**
  - Full-scale vehicle, at flight conditions (see table)
  - A ‘clean’ configuration, no protuberances except engine fairings

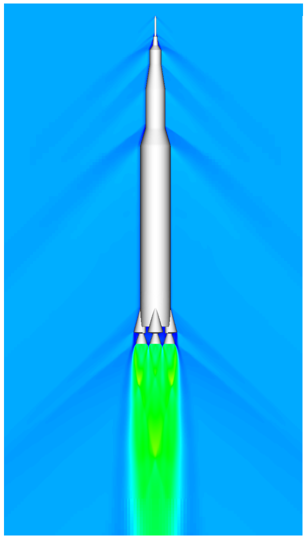
Table: Free stream conditions at four points in the Saturn V ascent trajectory (F. Canabal)

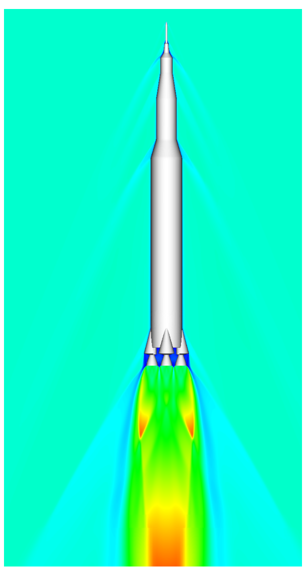
	M_∞	P_∞ (Pa)	T_∞ (°K)	Re_D
5 F-1 engines firing	1.5	12111.0	217	6.1522×10^7
	2.7	2250.0	221	2.2623×10^7
	4.4	151.0	264	1.6970×10^6
After Center Engine Cut-Off (CECO), only 4 engines firing	6.5	22.0	247	4.0600×10^5

Gusman, et al. AIAA, Jan. 2011, and Deere, et al. AIAA, Jan. 2011

Computed Results - PIFS on Saturn V

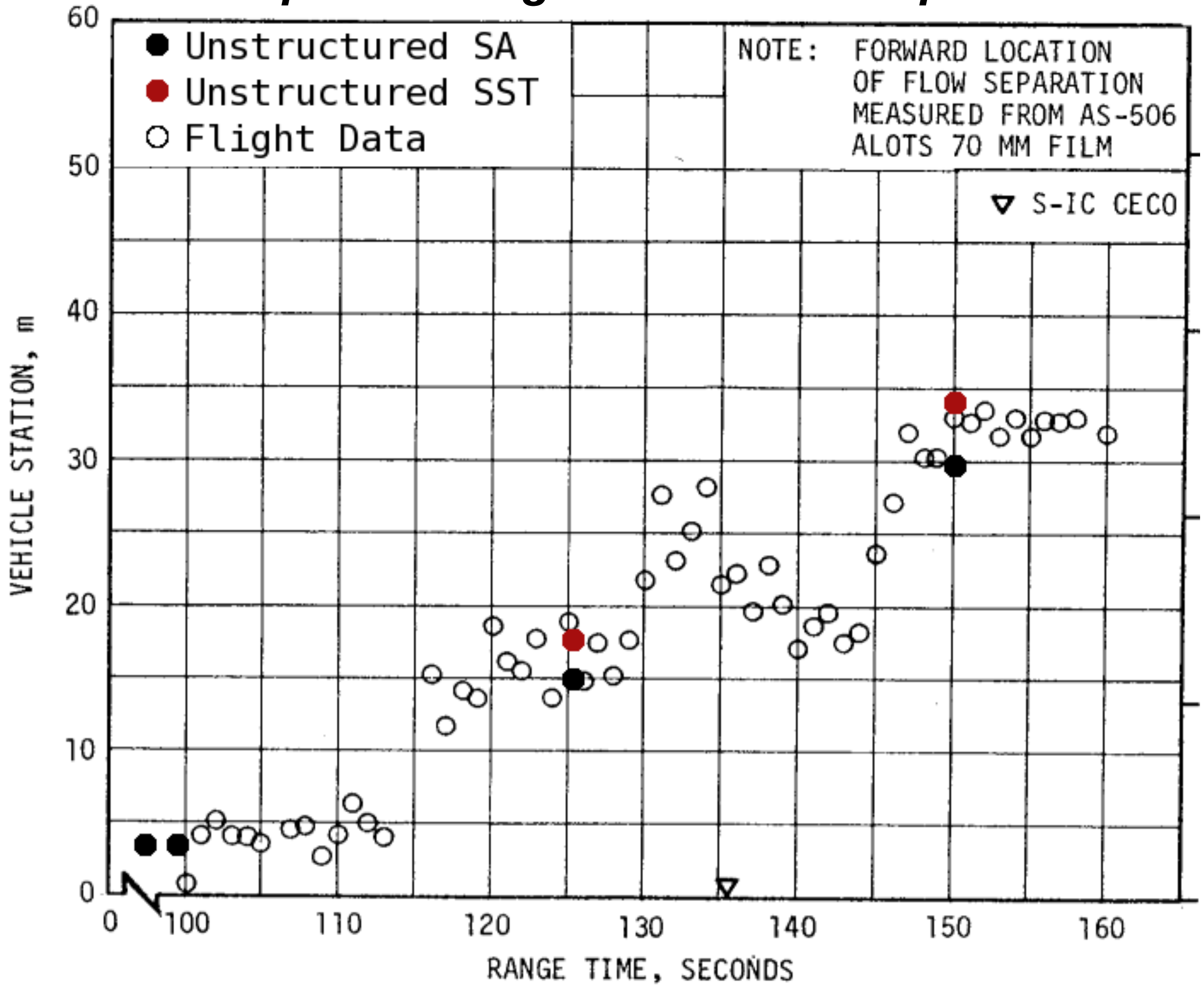
M = 1.5 at 80 sec

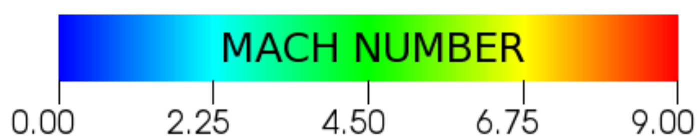




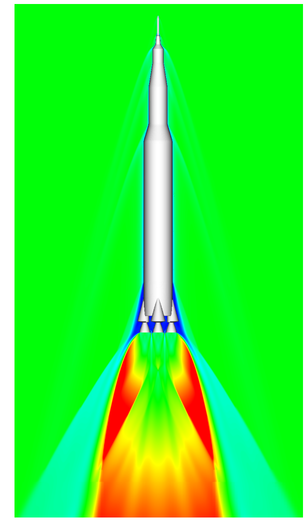
M = 2.7 at 100 sec

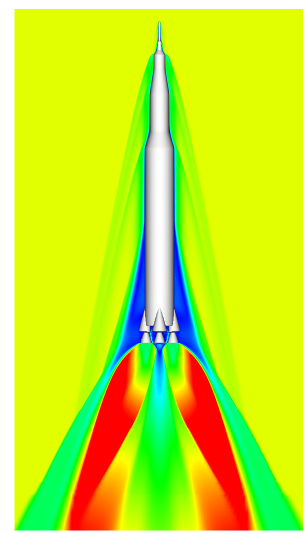
PIFS distance measurements from Apollo 11 Flight Evaluation Report





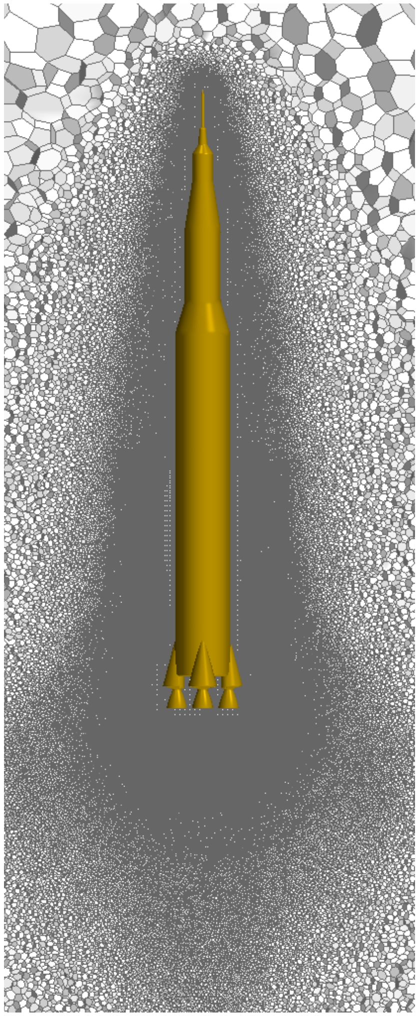
M = 4.4 at 125 sec



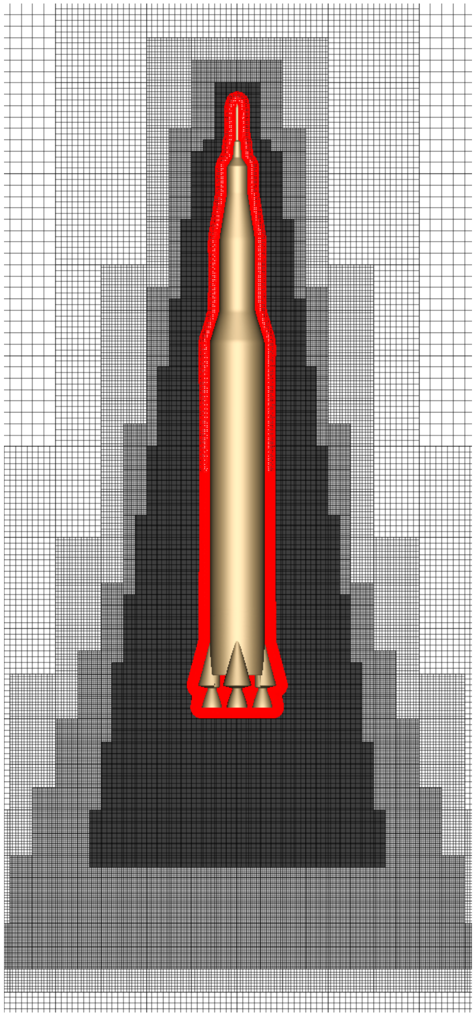


M = 6.5 at 150 sec

Grid Topologies for Saturn V PIFS

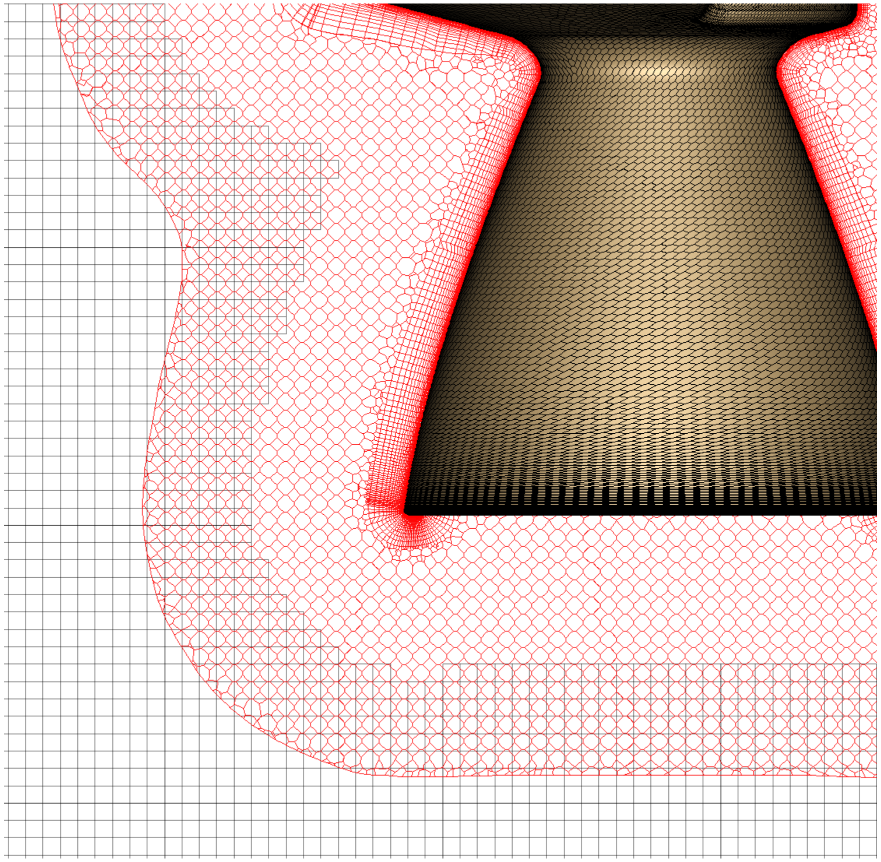


Stand-alone Unstructured Grid (40 M cells)



Unstructured (14 M) & Cartesian (98 M cells) Hybrid Overset Grid

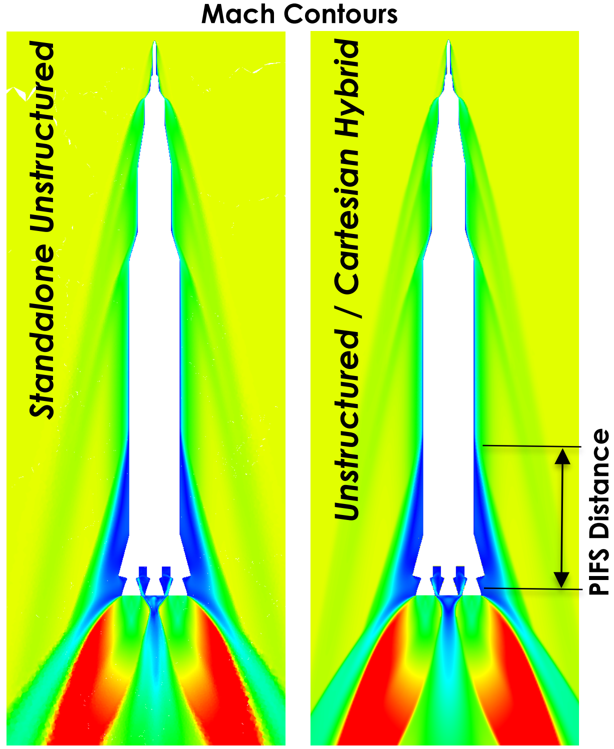
Hybrid Grid - close-up of nozzle

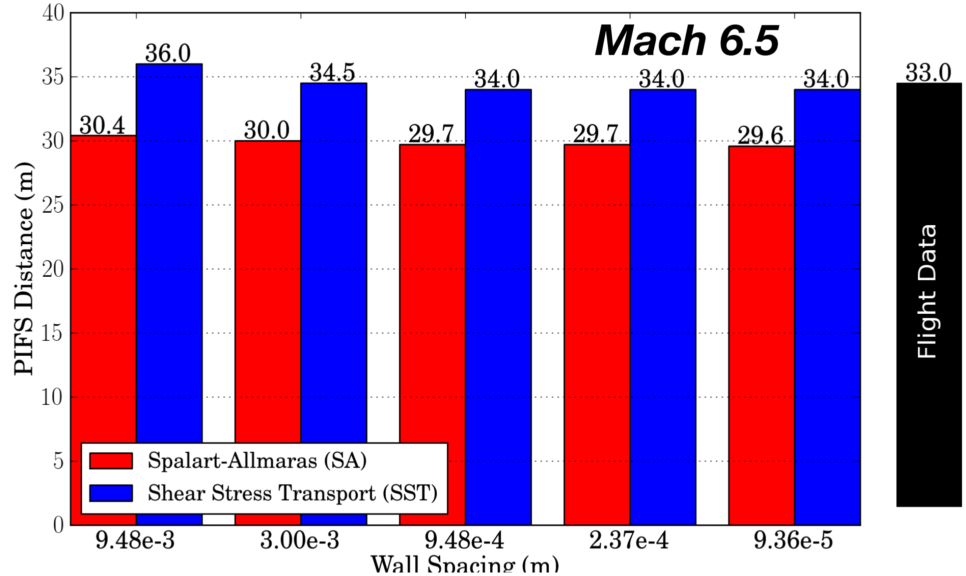


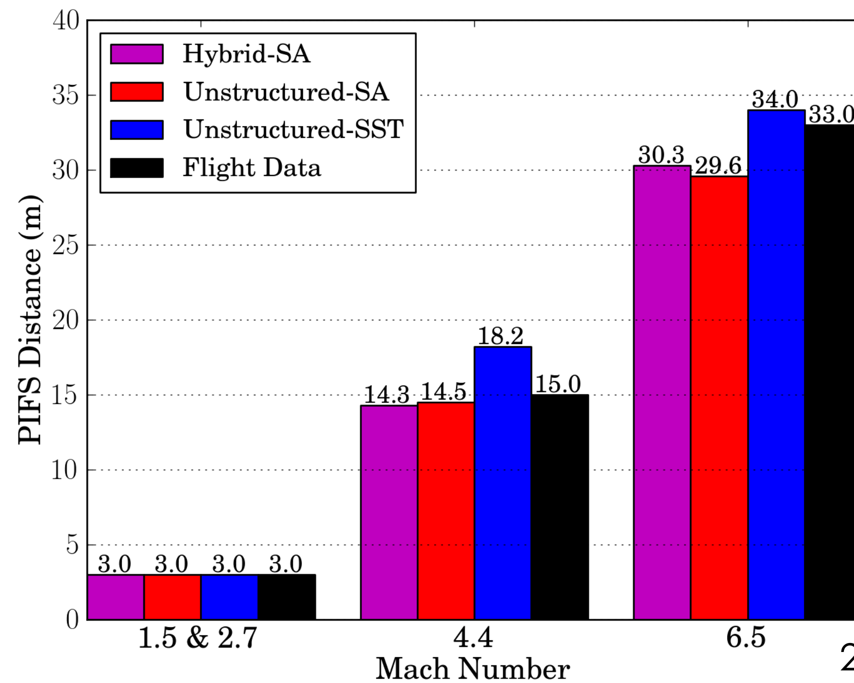
LAVA-Unstructured
Steady-State
AUSMPW+ Flux Vector Splitting
GMRES Linear Solver
Local CFL 20

Computed Results - PIFS on Saturn V

$M_\infty = 6.5$





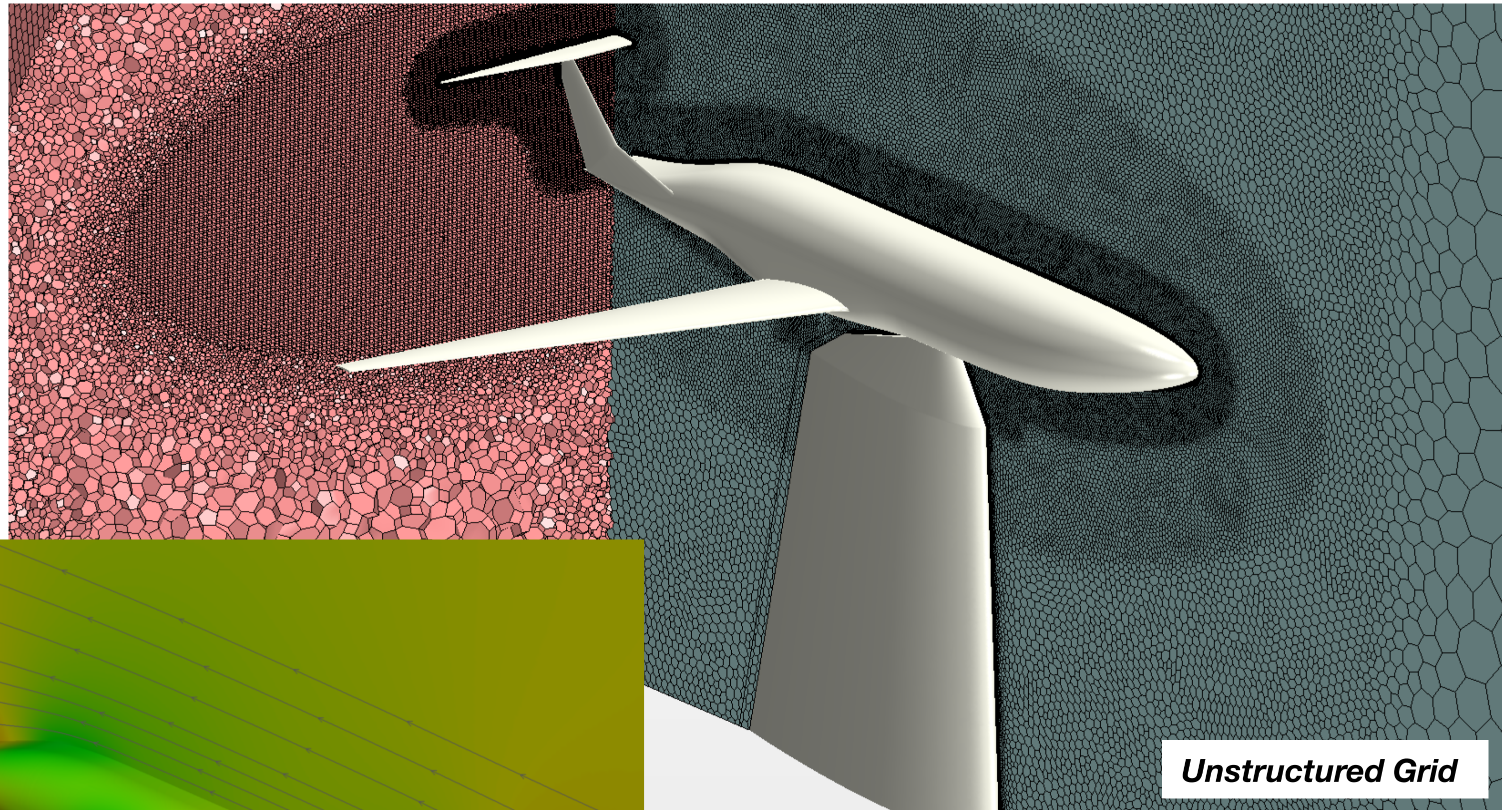


- A grid sensitivity study for wall normal spacing
- For M=6.5, grid convergence is achieved with a wall spacing 9.48e-4 m.
- Both hybrid and standalone PIFS results compare well with all four Mach numbers.

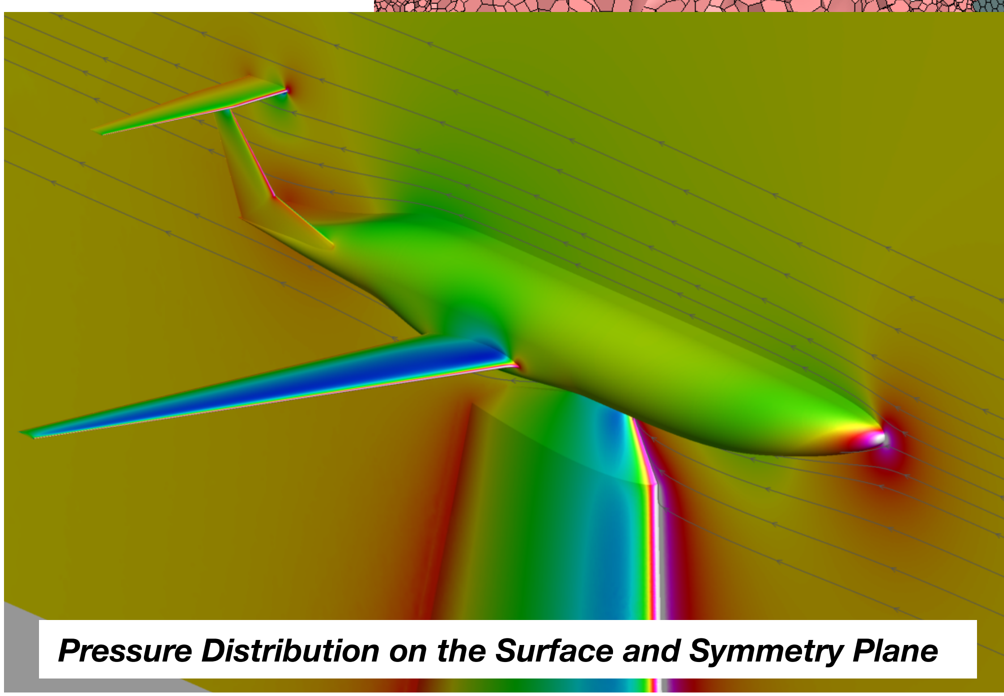
D8 "Double Bubble" Concept Aircraft

Fixed Wing Project in NASA's Fundamental Aeronautics Program

Pandya, et al.
ICCFD7, 2012



Unstructured Grid

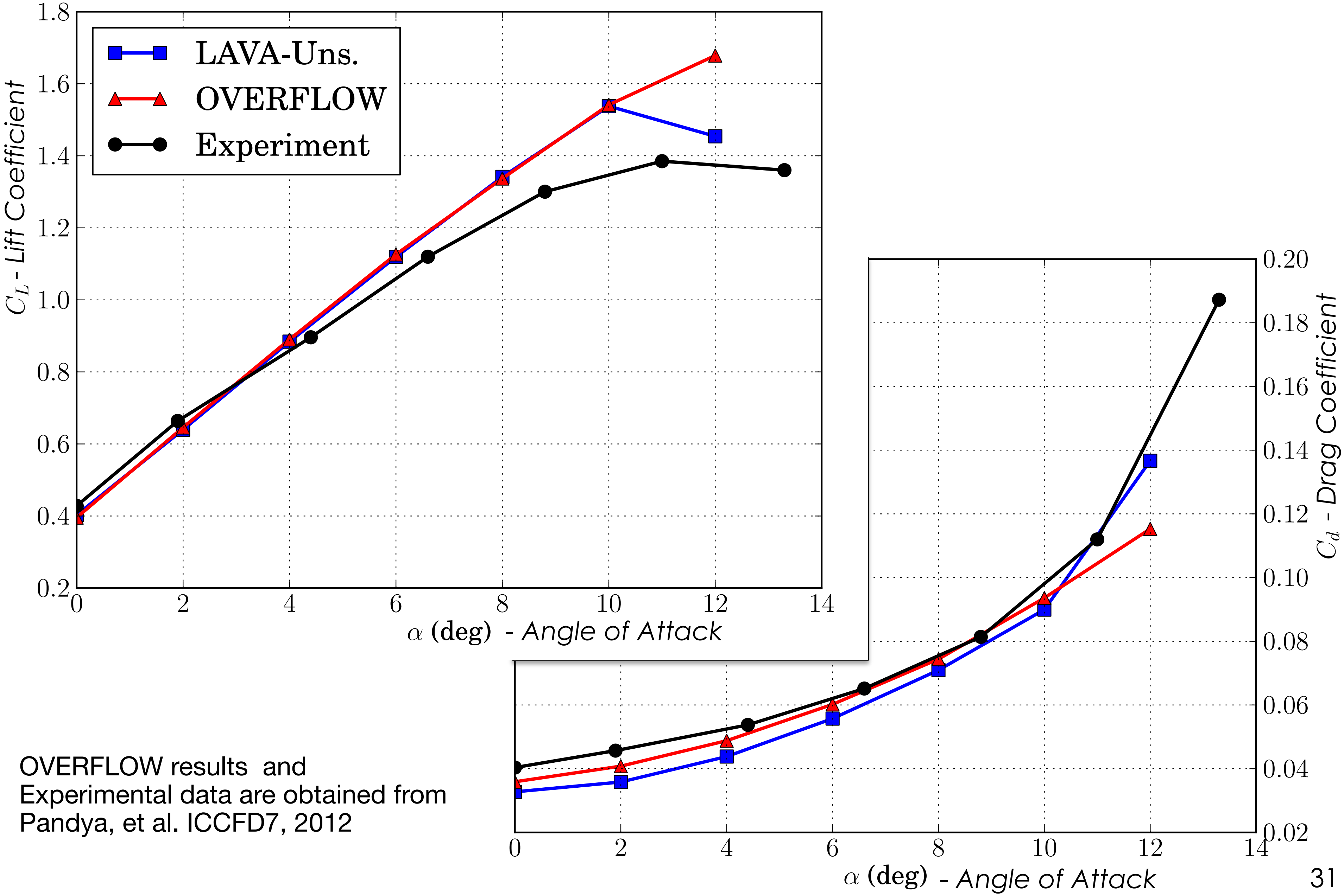


Pressure Distribution on the Surface and Symmetry Plane

Pandya et al**. AIAA 2014-0907**

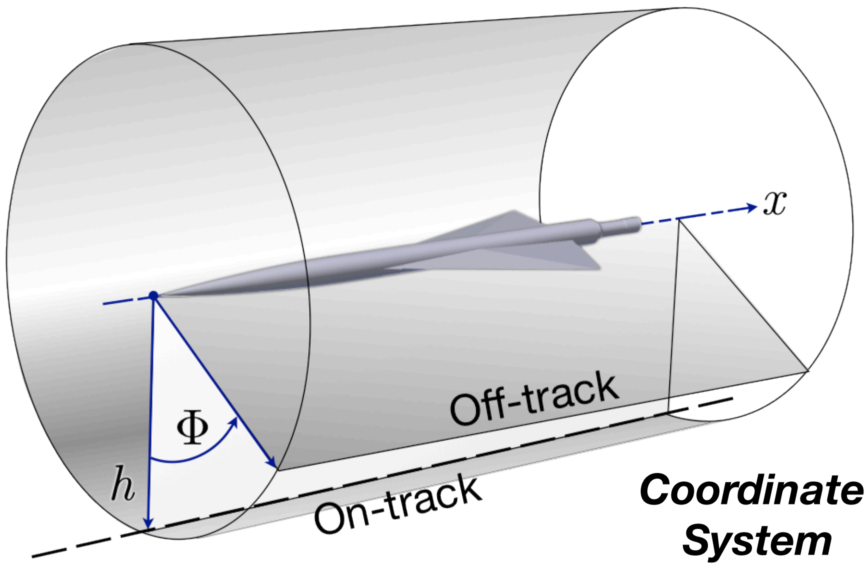
- Mach : 0.16
- Re : 3.117×10^{6} per meter
- 1:20 scale model wind tunnel test
- Arbitrary polyhedral unstructured grid with 18 Million cells
- SA one-equation turbulence model

D8 “Double Bubble” Concept Aircraft

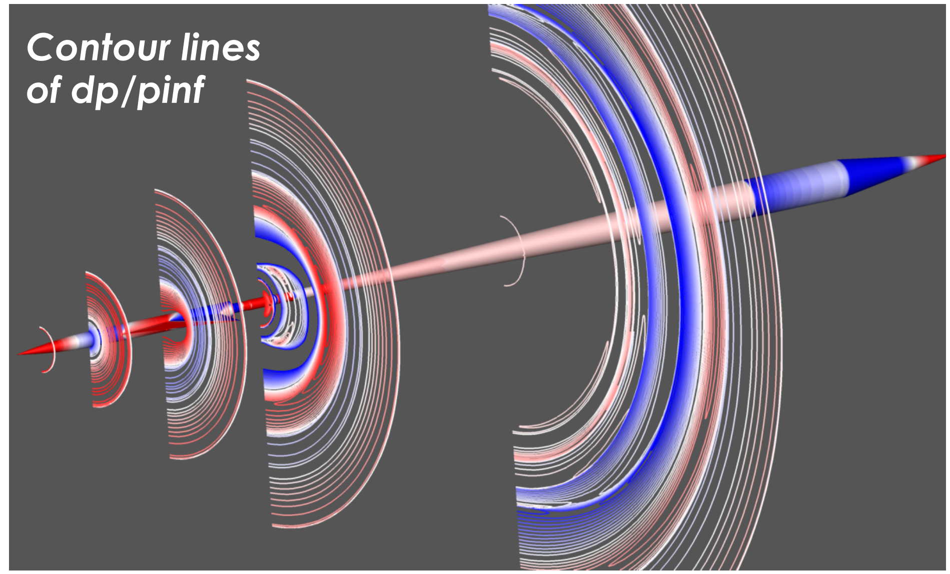


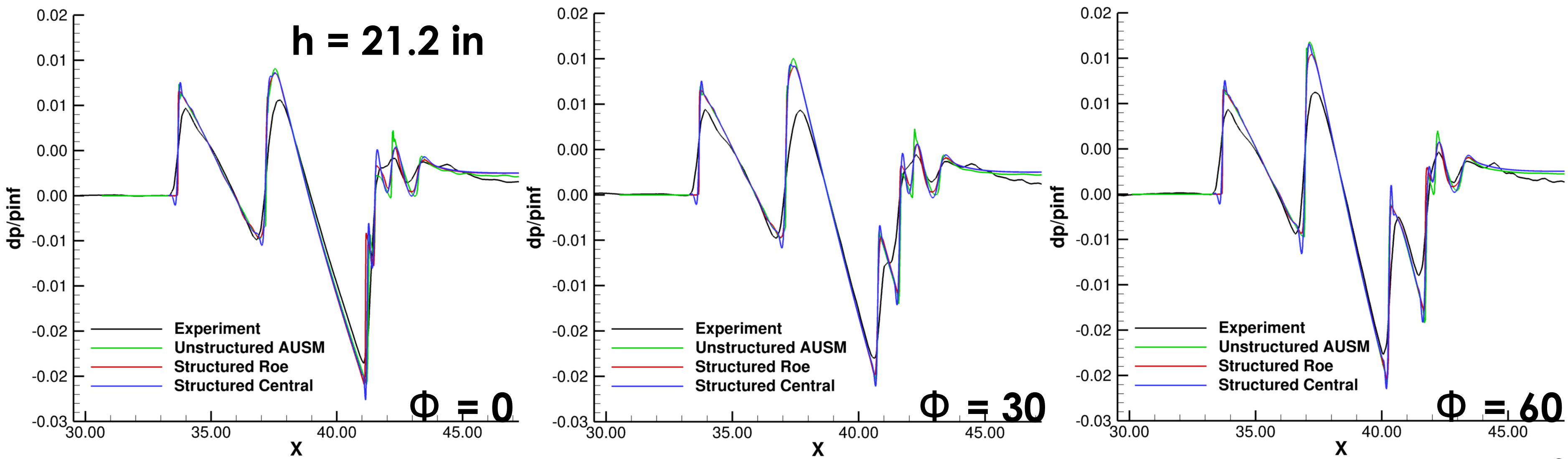
OVERFLOW results and Experimental data are obtained from Pandya, et al. ICCFD7, 2012

69-Degree Delta Wing Body: *Mach = 1.7, Re = 4.24x10^6 (per foot),α = 0 β = 0 deg.*



Coordinate System



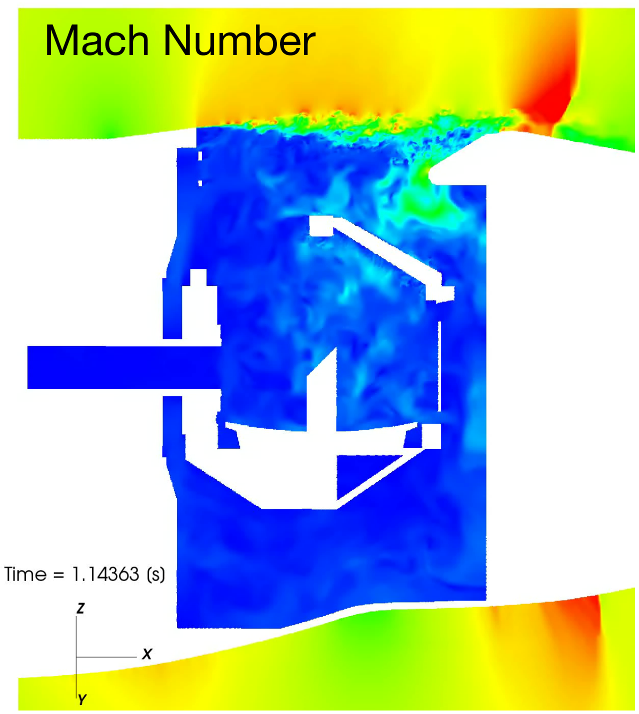


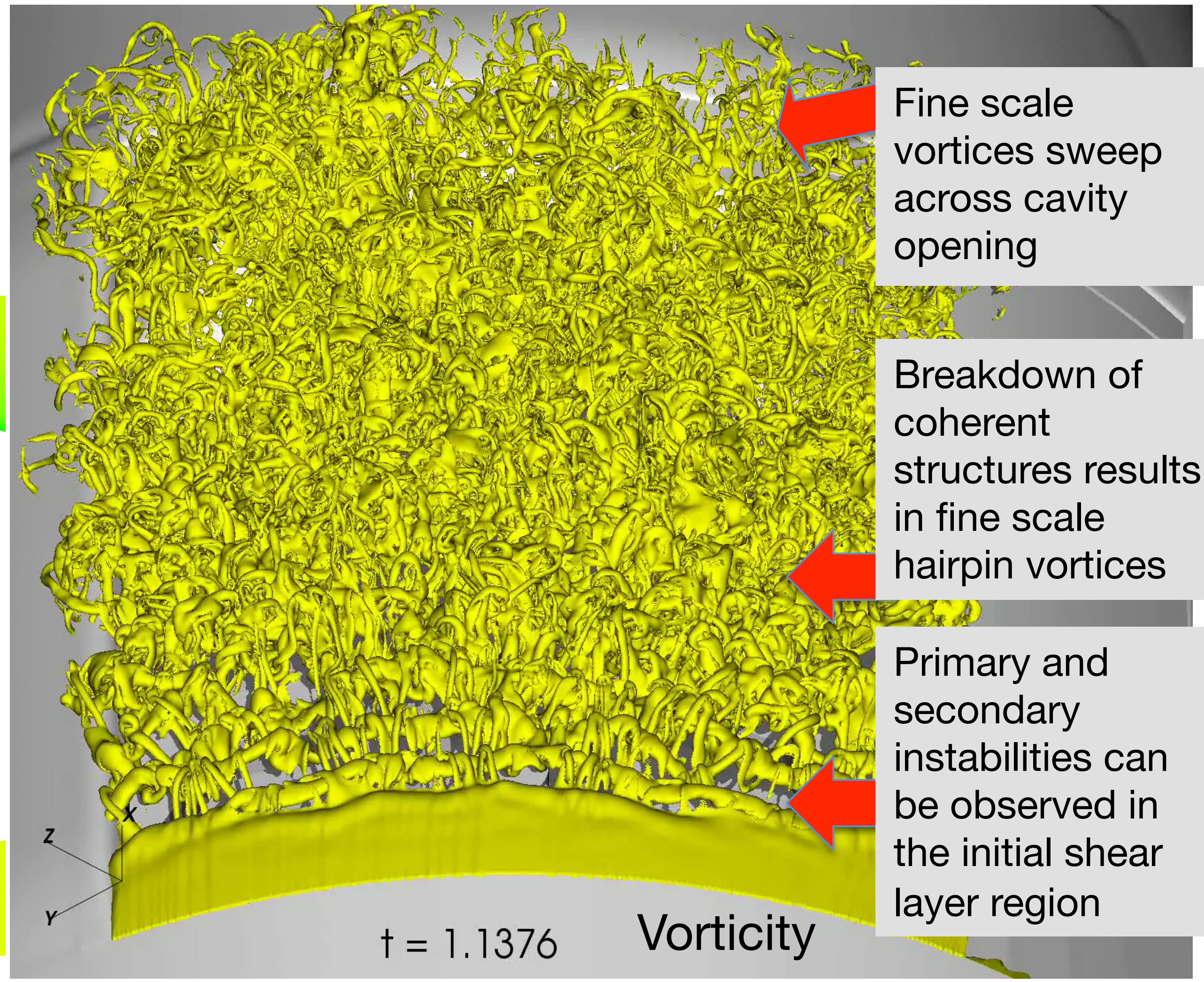
Housman at al. AIAA Aviation 2014, Aftosmis at al. **AIAA 2014-0558,** Cliff et al. **AIAA 2014-0560**

Simulations for SOFIA Cavity Acoustics

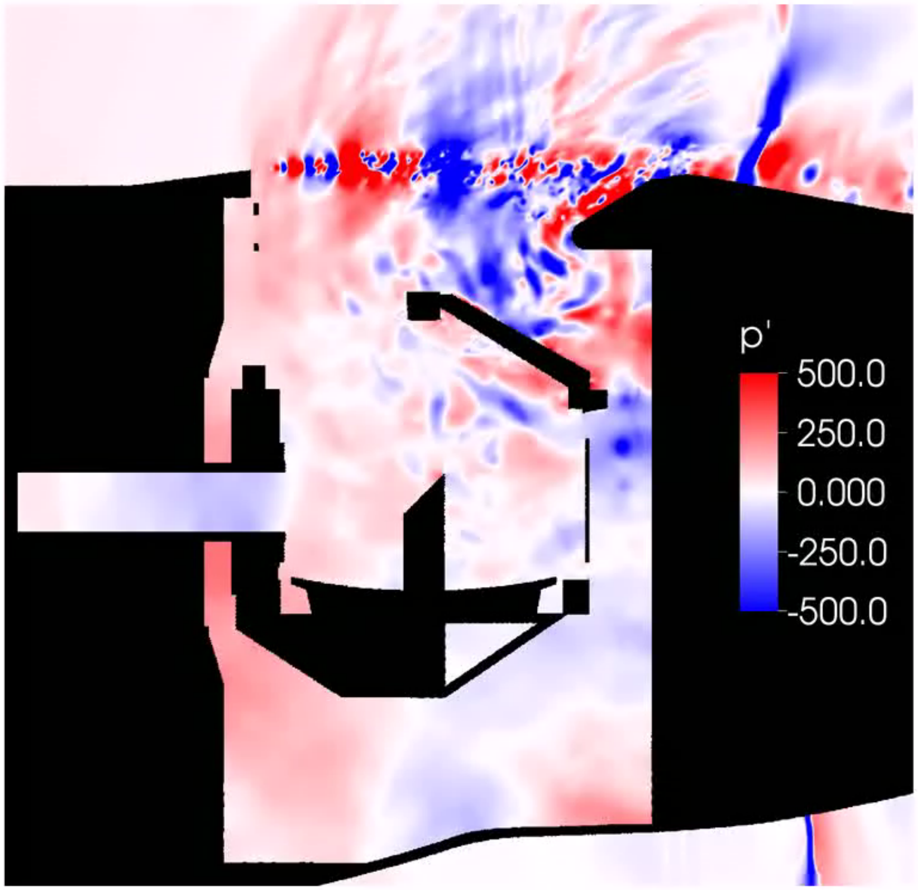
- Cruise at Mach = 0.88
- Immersed Boundary & AMR
- WENO5 with Explicit RK4 and ILES

- Noise levels comparable to flight levels inside the cavity (~120dB) .
- Excellent parallel scaling 400-32k cores



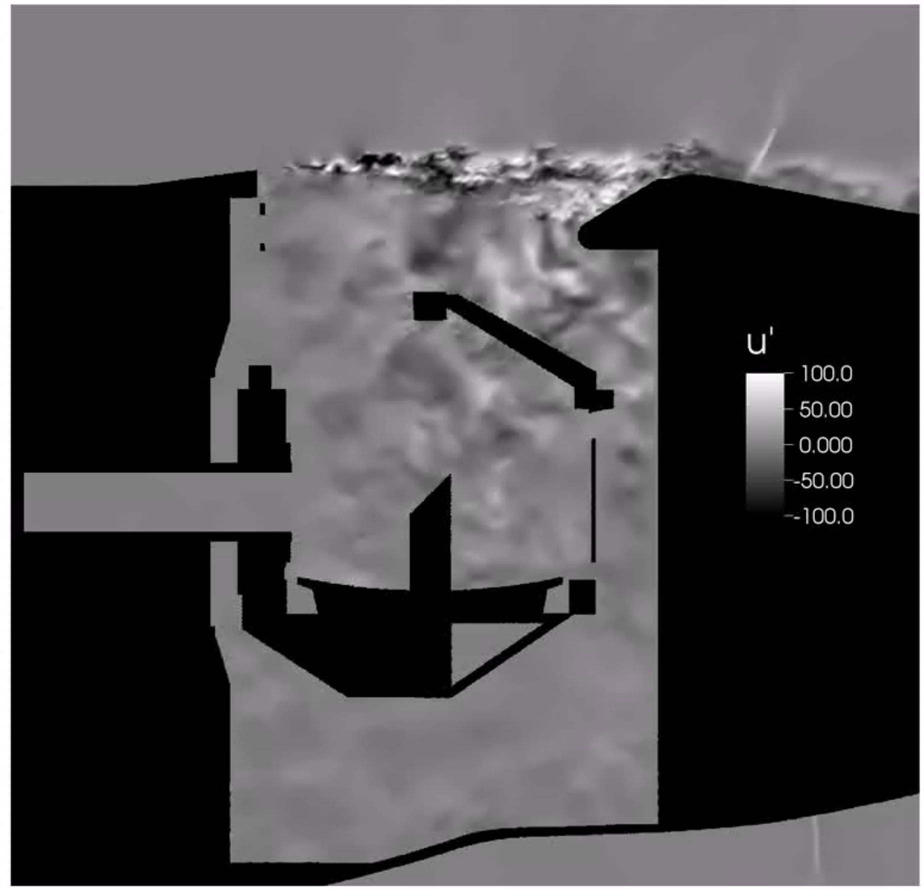


SOFIA CAVITY - DISTURBANCE FLOW FIELD



$$p'(t,x) = p(t,x) - \overline{p}(x)$$

- Acoustic radiation away from shear layer
- Unsteady pressure field inside cavity
- Interacting pressure field and shock



$$u'(t,x) = u(t,x) - \overline{u}(x)$$

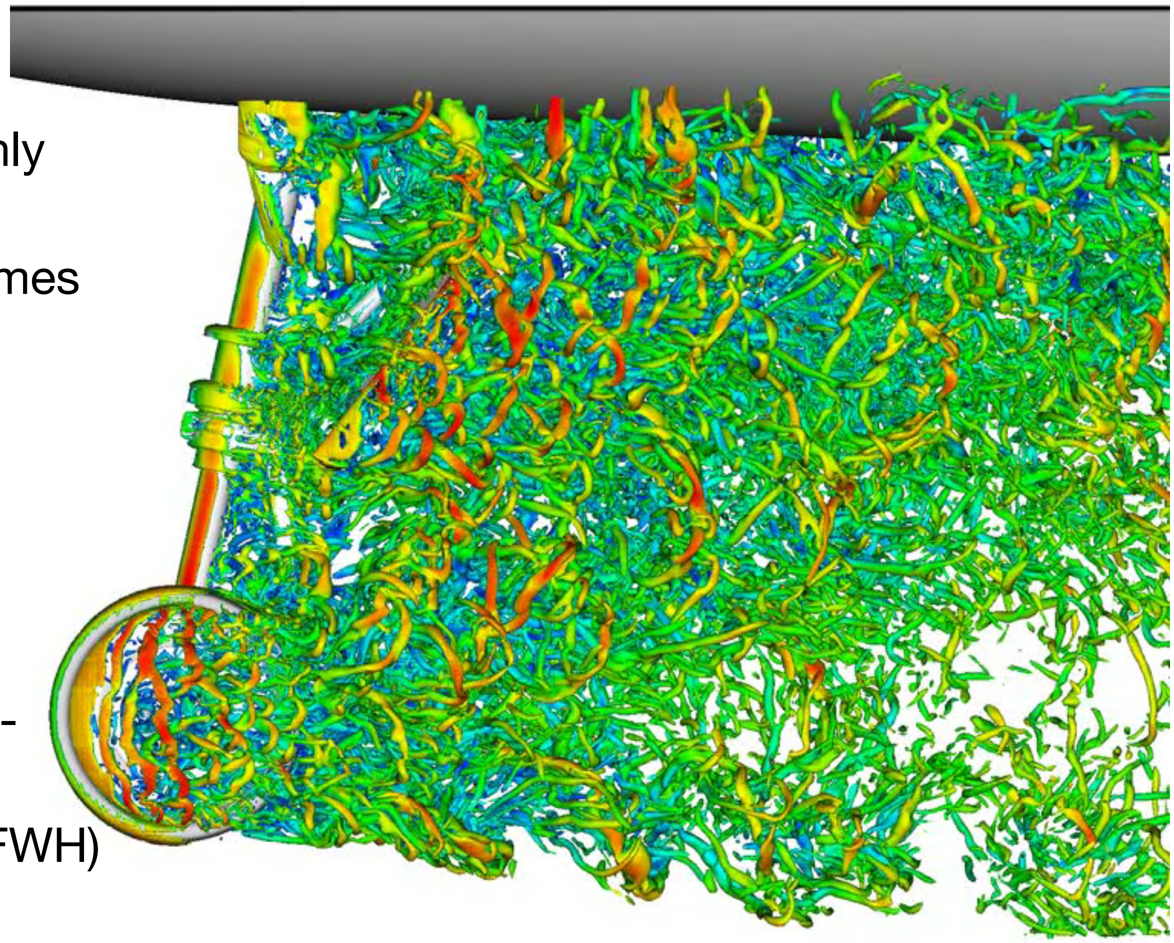
- Small scale velocity fluctuations
- Impingement of shear layer on vehicle
- Momentum transfer into cavity

AIAA BANC-III Test Case : Landing Gear

The LAVA solver was applied to a workshop Landing Gear problem

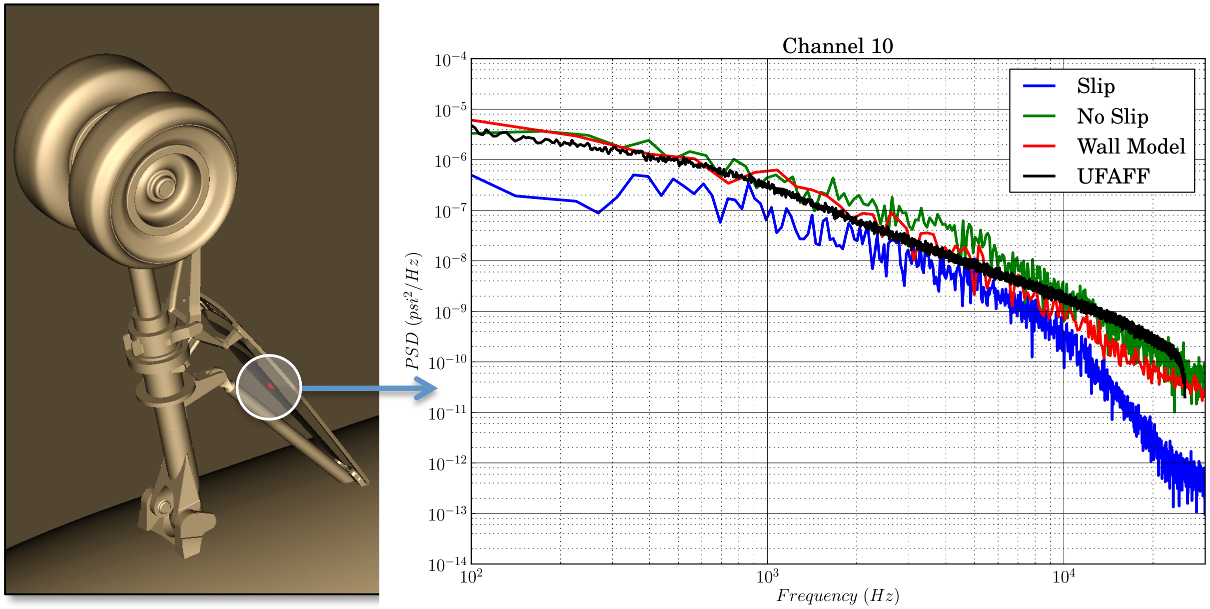
- Immersed-boundary (IB) utilized
  - Slip, no-slip, and wall modeled boundary conditions tested
  - Surface triangulation only requirement
- Higher-order accurate schemes
  - Fifth-order WENO Convection
  - 2nd order viscous (ILES)
  - 2nd order inter-level operators
- Time-accurate simulations
  - 4th order explicit Runge-Kutta
- Ffowcs William-Hawkings (FWH) noise propagation module

Mach = 0.166 Re = 73000	Uref = 56.3 m/s Tref = 286 K Pref = 99241 Pa

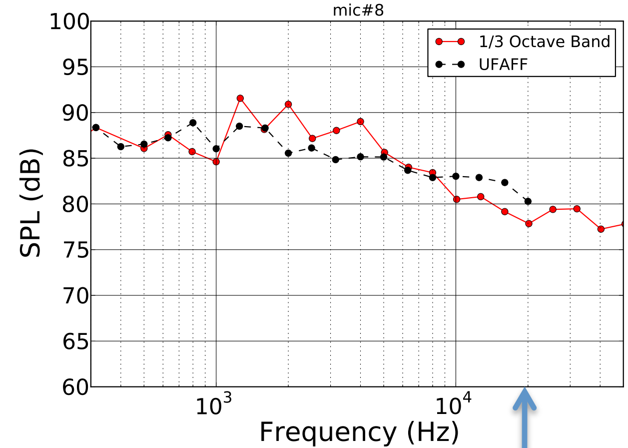


AIAA BANC-III Test Case : Landing Gear

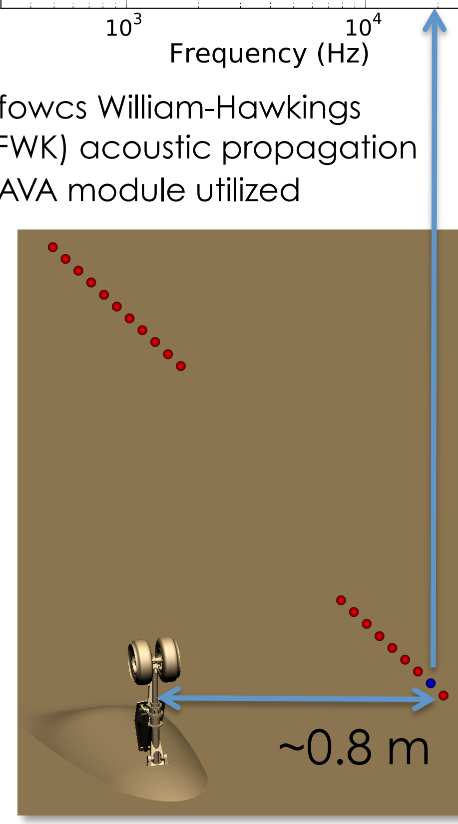
Power Spectral Density of Pressure



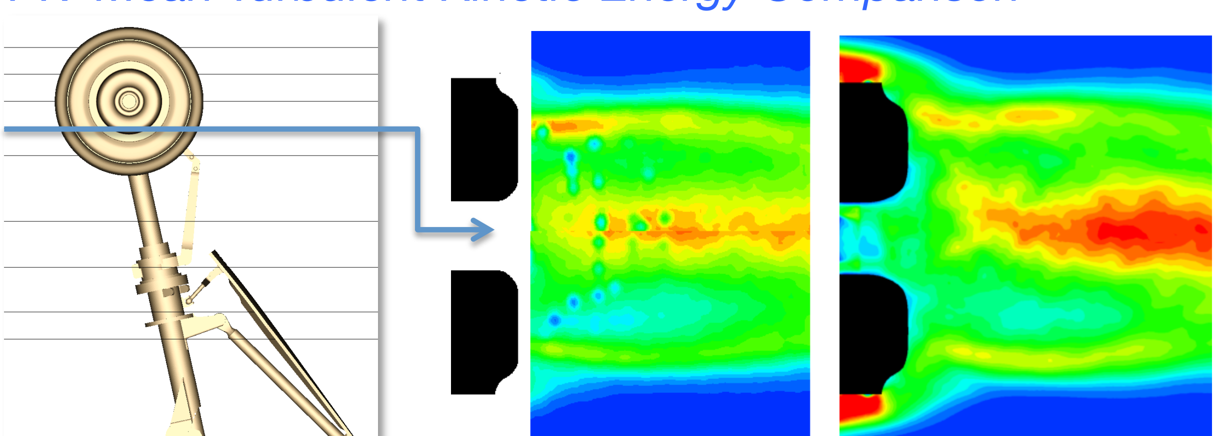
Far Field Acoustic SPL



Ffowcs William-Hawkings (FWK) acoustic propagation LAVA module utilized



PIV Mean Turbulent Kinetic Energy Comparison

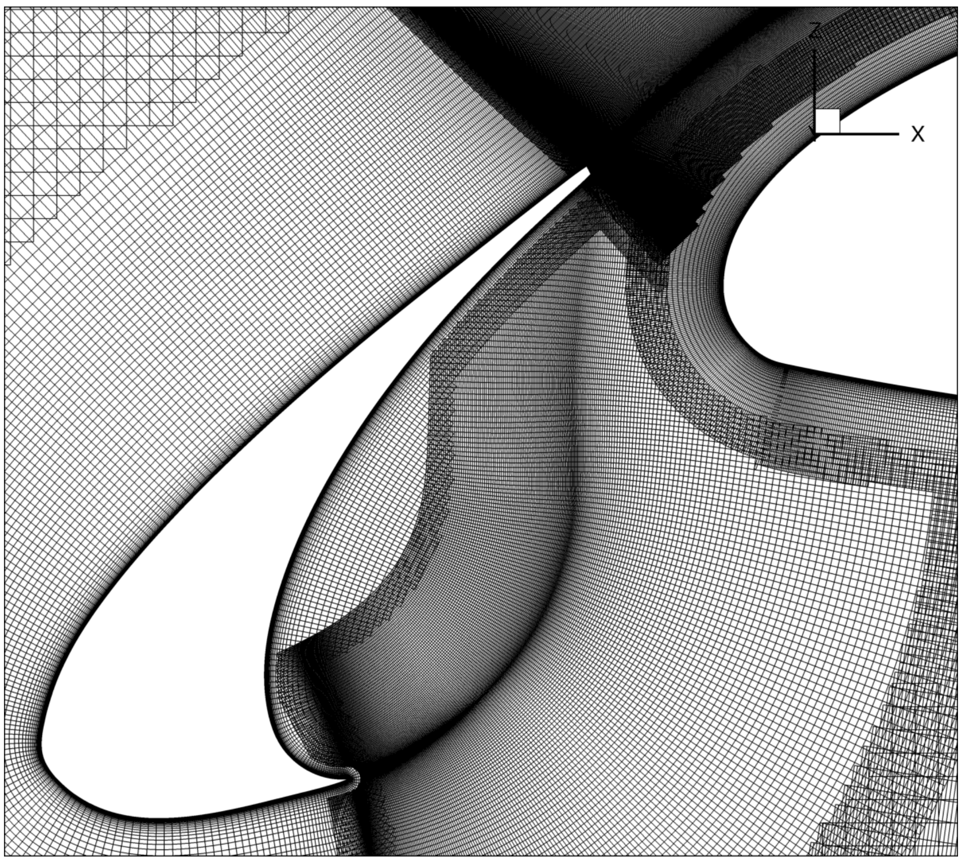


PIV LAVA

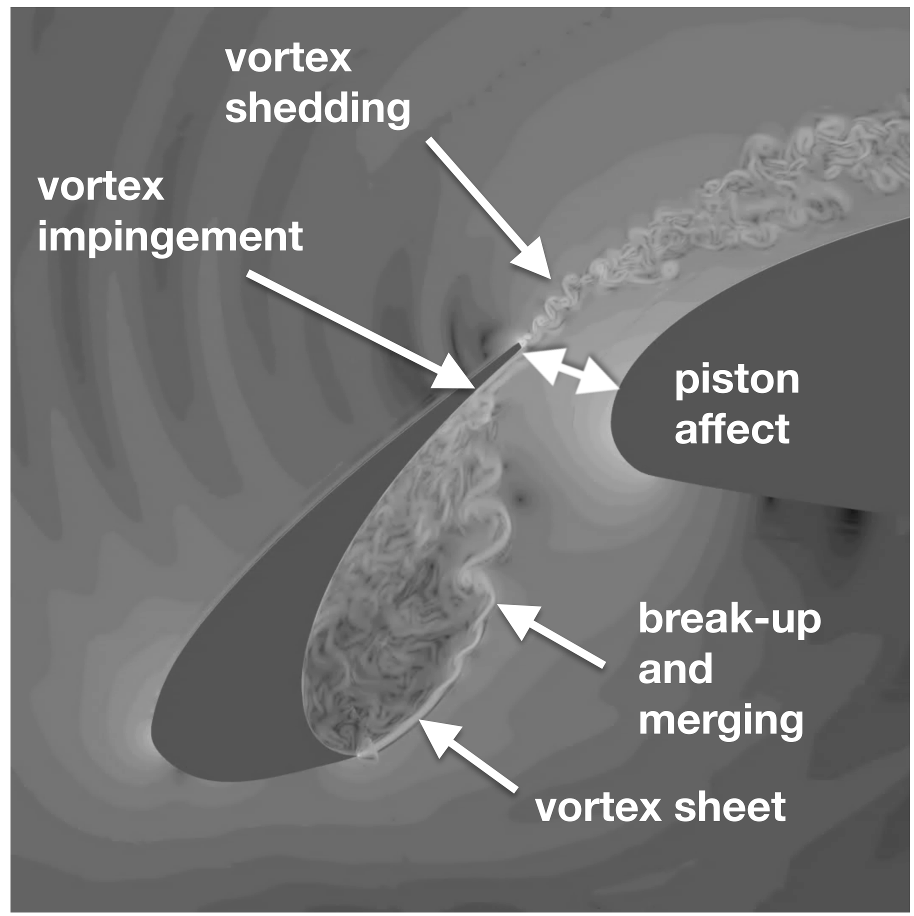
AIAA BANC-III Test Case : Slat Noise

- Goal is to assess the current capabilities of LAVA CFD/CAA tools applied to slat noise generation
- Flow physics is highly complex pushing the limits of current turbulence modeling and numerical methods

LAVA Overset-Structured

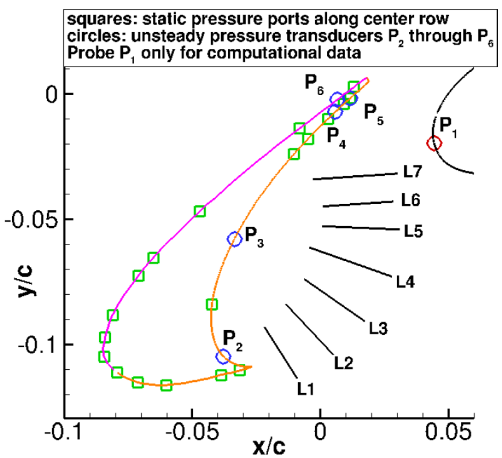


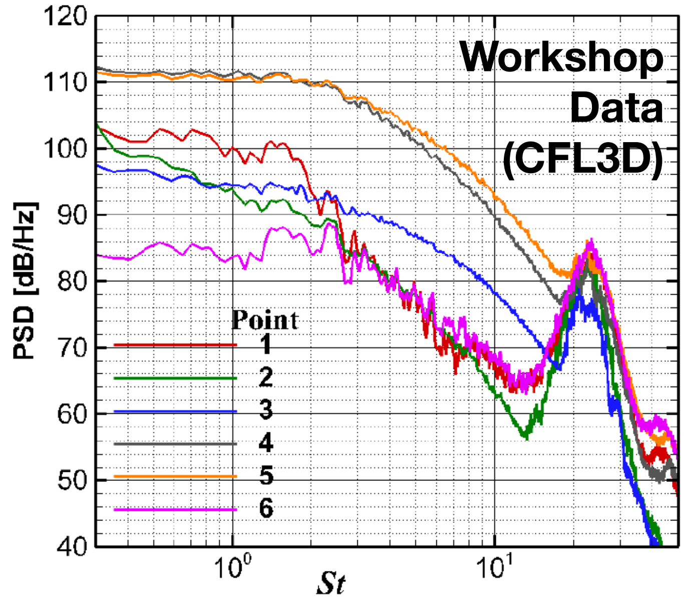
18 zones, 56.5 million grid points

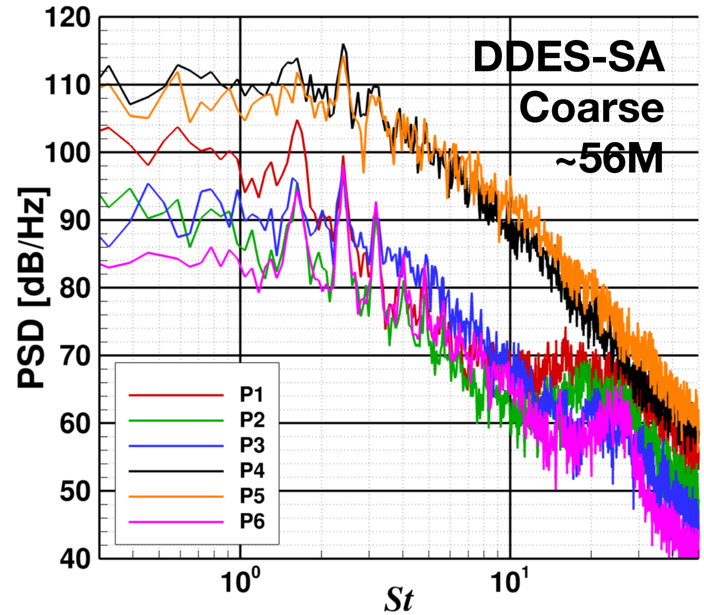


AIAA BANC-III Test Case : Slat Noise

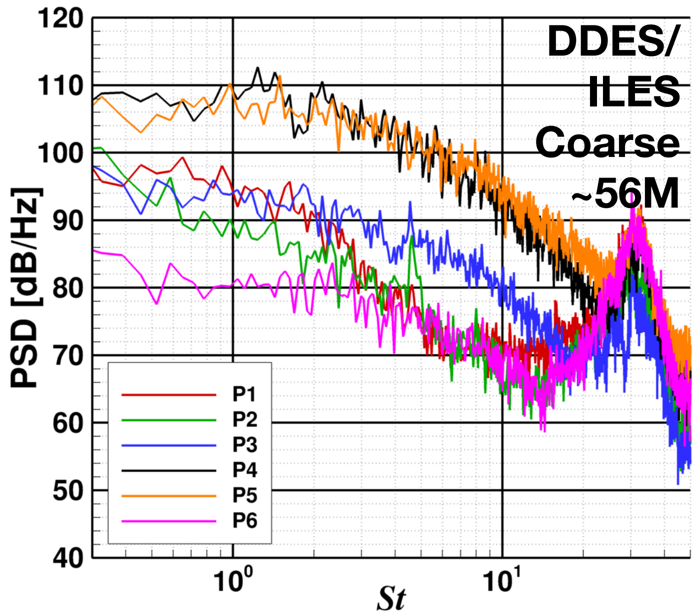
Near-Field PSD

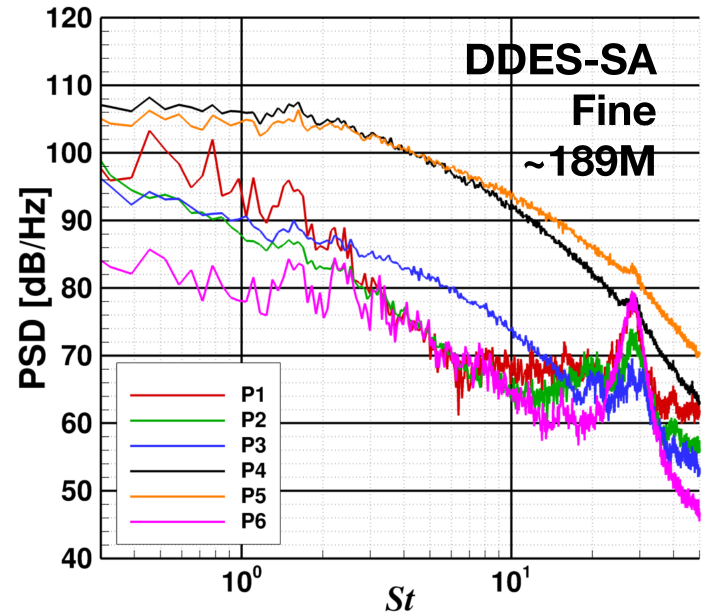






- Good match for
  St < 10
- Reduction of eddy viscosity using ILES or finer mesh necessary to resolve high frequency from slat trailing edge





Summary

- **Defining methods of LAVA have been outlined.**
  - Highly flexible grid approach (structured Cartesian, body-fitted unstructured and structured overlapping curvilinear)
  - Overset grid connectivity interface and immersed-boundary capabilities
  - Linear acoustic and conjugate heat transfer auxiliary modules
- **Contributions to NASA applications and mission related goals**
  - MFD Pressure environment using Cartesian IB-AMR method
  - MFD Thermal analysis using unstructured solver and conjugate heat transfer
  - Far-field jet acoustic prediction
  - Steady/unsteady SLS ascent aerodynamics prediction
  - Accurate Saturn V PIFS prediction
  - Accurate predictions of low speed and supersonic flow as well as acoustic field
- **Future Efforts**
  - Code optimization
  - Extend LAVA infrastructure
    - Coupling of body fitted grids through overset interface
    - 6-DOF body motion
    - Fluid-Structure interaction
    - Multi-physics models: multi-phase, combustion chemistry, etc.
  - Interface with other solvers and frameworks